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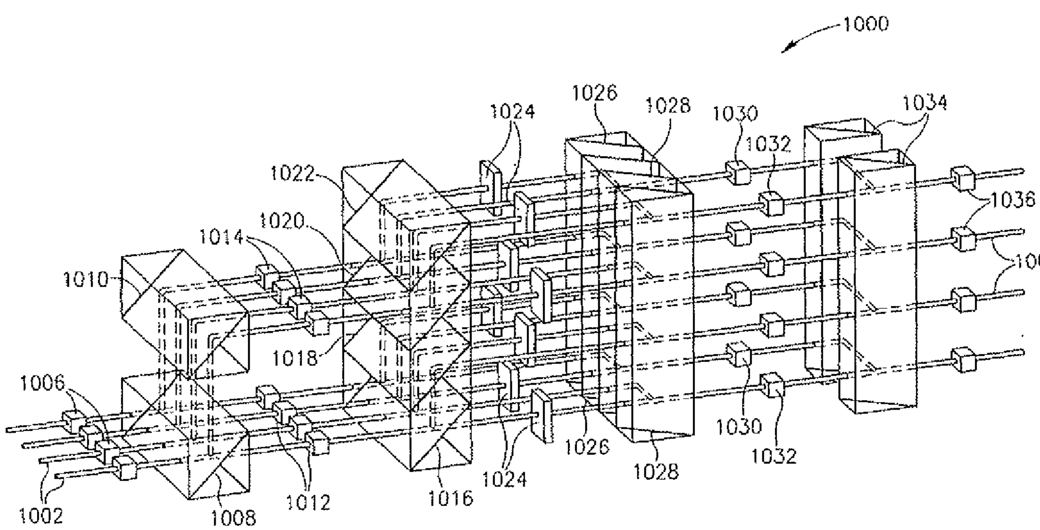


(57) Abstract: An optical router-selector comprising: at least four channels, including at least one input channel and at least one output channel; a plurality of optical junction elements controllable to direct light from any input channel to any of the at least one output channels, wherein each element couples three optical paths, and comprises at least one controllable polarization rotator, the state of which determines whether and how much of light entering one of the paths exits through at least one of the other paths; and a controller which controls the state of each controllable polarization rotator, wherein the controller is configured to control all of the members of at least one set of two or more of the controllable polarization rotators to be in a same state at a given time.

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# FAST ALL-OPTICAL SWITCHES AND ATTENUATORS

## RELATED APPLICATIONS

The present application claims the benefit under 119(e) of US provisional application No. 60/263,333 filed January 22, 2001, and US provisional application No. 60/306,070 filed July 17, 2001, and is a continuation-in-part of US application No. 09/907,252 filed on July 17, 2001, and PCT application No. PCT/US02/01820, filed January 22, 2002, the disclosures of which are incorporated herein by reference.

## FIELD OF THE INVENTION

The present invention is related to the field of optical communication and computation networks.

## BACKGROUND OF THE INVENTION

As the size and speed limits of semiconductor technology are approached, optical networks provide an attractive alternative for communications and computation. Optical networks require switches for switching an optical signal between two or more outputs, as well as multicasters for distributing an optical signal to more than one output, and attenuators for reducing the amplitude of an optical signal. It is desirable for these elements to be all-optical, working directly with the optical signal, rather than converting it into an electronic signal and back into an optical signal.

US patents 5,363,228, 5,414,541, and 6,041,151, the disclosures of which are incorporated herein by reference, are examples of implementations of an all-optical switch. The device described by US patent 5,414,541 is a 1x2 switch, in which the light from one input channel is passed to either one of two output channels. The input channel can have any polarization state, and the output channel into which each input channel is directed has the same polarization state as the input channel. The term "polarization state" as used here includes not only any state of pure linear, elliptical or circular polarization, but also unpolarized light, and any degree of partial polarization.

The light from the input channel is passed through a polarizing beam splitter, for example a crystal of calcite, and separated into two beams of orthogonal pure polarization states, for example vertical and horizontal linear polarization. One of the beams then passes through an element which changes its polarization to be the same as the other beam. This element, for example, could be a half-wave plate of a birefringent material with its principal axis oriented at an angle of 45 degrees to the polarization of the beam, which will convert horizontally polarized light to vertically polarized light.

The two beams, now with the same polarization, are then passed through a controllable polarization rotator, which rotates the polarization by an amount that can be controlled externally. For example, a ferroelectric crystal can be used, which has a degree of birefringence that depends on the electric field that is applied to it. If no electric field is applied, then the controllable polarization rotator is inactive, and light passes through it with no change in its polarization. If an electric field of a particular direction and magnitude is applied to the ferroelectric crystal, then the controllable polarization rotator is active, and the polarization of the light changes its direction by 90 degrees when passing through it. The light is then passed through another polarizing beam splitter, which either allows the light to go straight through, or displaces it to the side, depending on the polarization of the light. If the controllable polarization rotator is inactive, then the light emerging from the second polarizing beam splitter will be directed toward the first output channel. If the controllable polarization rotator is active, then the light emerging from the second polarizing beam splitter will be displaced toward one side, and will be directed toward the second output channel.

If an electric field is applied to the controllable polarization rotator, but less than the full field needed to rotate the polarization by 90 degrees, then part of the light from the input channel will go into one output channel, and part of the light will go into the other output channel. The amount of light going into each channel is controlled by controlling the electric field in the controllable polarization rotator. The 1x2 switch is thus used as a multicaster.

US patent 5,363,228 describes an all-optical cross-bar switch, using similar methods, in which each of N input channels can be directed to any of M output channels. This device suffers from various drawbacks. For example, since it uses polarization separation, 2n optical paths are required, where n is the number of input ports. In addition, complicated manufacturing and fine alignment is required.

US patent 6,041,151 describes a bypass-exchange switch which operates in a similar fashion to the 1x2 switch described in US patent 5,414,541. This bypass-exchange switch has two inputs and two outputs, and the two inputs are always directed to different outputs.

## SUMMARY OF INVENTION

An aspect of some embodiments of the invention concerns all-optical router-selector networks, used as switches and/or as multicasters, and/or as combiners and/or as variable attenuators. A variable attenuator may be used as a shutter. In a switching network, each of a number ofinput channels is connected to any one of the same number or a different number of output channels, but no more than one input channel is connected to each output channel, and no more than one output channel is connected to each input channel. In a multicasting network,

each input channel may be connected to more than one output channel, and in a combining network each output channel may be connected to more than one input channel. A single network may include more than one mode of operation, for example both multicasting and switching. In some embodiments of the invention, the signal in each input channel in a multicaster may be divided among two or more output channels with an arbitrary ratio of power going into each output channel, and in some embodiments of the invention the signal in one or more output channels may be attenuated to an arbitrary degree, optionally leaving each output channel with a different attenuation, optionally within upper and lower limits. Similarly, in some embodiments of the invention the signal in each output channel in a combiner may come from two or more input channels with an arbitrary ratio of power.

In an embodiment of the invention, such an optical network, whether used for switching, multicasting, combining, or attenuating is built up of polarized beam splitters (which can be, for example, periscopes, as described below, or calcites), and controllable polarization rotators. As used herein, "calcite" means any material with birefringent properties which give it similar functionality to calcite, including synthetic materials such as yttrium vanadate ($YVO_4$).

In a router selector network, according to an embodiment of the invention, each input signal is repeatedly switched, or (in the case of a multicaster) divided between two paths, in the router section, until the number of paths for that input channel is equal to the number of output channels. For example, N stages in the router section may be used to switch each input channel into any one of $2^N$ output channels. The different paths coming from different input channels into the same output channel are then repeatedly combined in pairs, in the selector section, until only one path remains for each output channel. For example, M stages in the selector section may be used to direct any one of $2^M$ input channels into each output channel. In an optical network, the switching, multicasting or combining of the signal at each junction may be accomplished by a controllable polarization rotator and a calcite.

An aspect of some embodiments of the invention concerns a router-selector in which each junction does not have its own controllable polarization rotator, but several junctions share a same controllable polarization rotator. For example, if the network is a switching network (not multicasting or combining), then only one controllable polarization rotator is required for all of the junctions associated with each input channel at each stage in the router, and only one controllable polarization rotator is required for all of the junctions associated with each output channel at each stage in the selector.

An aspect of some embodiments of the invention concerns an optical switch or another optical configuration in which components, which are to be aligned, are mounted on rotatable bearings, such as ball and socket bearings. The components could include, for example, optical fibers for the input and output channels, polarizing beam splitters, and controllable polarization rotators. Misalignment of any of these components could result in the beam from an input channel missing the output channel that it is meant to be switched to, or could result in increased attenuation or cross-talk. These components are aligned, for example by hand or machine, and when alignment is achieved, an adhesive in the bearing is cured, for example using ultraviolet light, fixing the bearing in place. The adhesive can be applied to the bearing before or after the components are aligned. Optionally, if the adhesive is applied before the components are aligned, it has low enough viscosity that it will not hinder the alignment. In some embodiments of the invention, the mounting only has one rotational and one translational degree of freedom. In some embodiments of the invention there are adjustable limits on one or more of the degrees of freedom. This makes it possible, for example, to coarsely adjust one of the degrees of freedom first, and then limit the range of motion of that degree of freedom, before making a fine adjustment.

An aspect of some embodiments of the invention concerns one or more optical components which act as a bearing. For example, the bearing comprises a convex lens with spherical surface, which fits against a concave lens with matching spherical surface, and the lens slip relative to each other while their surfaces stay in contact, similar to the action of a ball and socket joint, thereby changing the alignment of a light beam passing through the lenses, or through other lenses or other optical components which are mounted on the bearing.

An aspect of some embodiments of the invention concerns a bearing to which a curable adhesive is applied, the bottom of which bearing has one or more grooves in it, so that excess adhesive can drain away. A uniform layer of adhesive is formed, and the adhesive will not interfere with the parts of the bearing (for example, a ball and a socket) fitting together properly.

An aspect of some embodiments of the invention concerns a polarizing beam splitter in the form of a periscope. A periscope is a structure with a place for light to enter, a place on the other side for light to exit, and two reflectors, generally parallel to each other, which the entering light reflects from, so that the light exits the periscope going in the same direction as it entered, but laterally displaced. In the case of a polarizing beam splitter periscope, all of the light is not reflected at the reflectors, but some of it is transmitted through the reflectors. Light entering the periscope at the bottom strikes a transparent plate with an optical coating, for

example a multi-layer optical reflective coating (whose reflection may be wavelength dependent), oriented at 45 degrees to the direction of the light, and either is reflected upward, or goes straight through and exits the periscope, depending on its polarization. The plate could be oriented at an angle other than 45 degrees, in which case the reflected portion will be deflected by an angle other than 90 degrees, and prisms and other optical elements could be used, and multiple beams could be created. However, a simple coated plate at 45 degrees is best for many applications.

The light reflected upward strikes another plate, optically coated as before, and generally parallel to the plate at the bottom. Although the second plate need not be parallel to the first plate, if it is parallel then the beam reflected from the second plate will be parallel to the light entering the periscope. Because this light is already polarized, most of it reflects from the second plate, and emerges from the periscope at the top, traveling parallel to the light that emerges at the bottom. A small amount of light that is polarized in the "wrong" direction will not reflect from the plate on the top, but will go straight through it, and will be lost. Optionally, an absorber mounted on or above the top of the periscope absorbs this light, to prevent it from being scattered and having some of it eventually getting back into the system. Hence the light emerging from the periscope at the top will have an even higher degree of polarization than the light reflected from the first plate. In an exemplary embodiment of the invention, the amount of contamination is 1%, 5%, 10%, 20% or any smaller, greater or intermediate percentage of the desired light power. The degree of reduction may be, for example, 50%, 80%, 90%, 95%, 99% or any smaller, intermediate or greater percentage.

The periscope serves the same function as a calcite crystal, splitting a beam of light into two beams of orthogonal linear polarizations. But the periscope is more compact and has a smaller footprint, since calcite only displaces light (of one polarization) by a small angle, and a long calcite crystal is needed to produce a reasonable lateral displacement of the light. On the other hand, the optically coated plates used in the periscope only work well for a limited range of wavelengths, while a calcite crystal (or a synthetic crystal with similar properties, such at yttrium vanadate) works over a broader range of wavelengths. This limitation of a periscope to a narrow range of wavelengths depends on the embodiment used, and a periscope may work over a broader range of wavelengths if unwanted paths are blocked, as described below. Optionally, instead of using a second optically coated a plate, a mirror is used to direct the reflected beam in the same direction as the transmitted beam. Optionally, after reflecting from the mirror, the beam passes through a polarizer to block the small amount of light that is polarized in the wrong direction. Optionally, the light that is transmitted through the optically

coated plate at the entrance to the periscope also passes through a polarizer, to block the small amount of that light which is of the polarization that should be reflected. A periscope, like any polarizing beam splitter, can be used in reverse, to combine two beams of different polarizations to form a single beam.

In an exemplary embodiment of the invention, pairs of beams with different initial polarizations are converted to beams with same polarization that can travel close together so they can share optical elements.

Another aspect of some embodiments of the invention concerns an all-optical variable attenuator, or an all-optical switch which includes a variable attenuator. If the light in one of the output channels of a 1x2 switch is absorbed or otherwise discarded, then the device is a variable attenuator, modulating the intensity of the light beam at frequencies up to the maximum operating frequency of the controllable polarization rotator. To build a 1x2 switch with controllable attenuation of each output channel, one could attach two such stand-alone variable attenuators to the output channels of a 1x2 switch. However, there is an alternative embodiment in which a variable attenuator is incorporated into a 1x2 switch, such as that described in US patent 5,414,541, which is simpler than adding two stand-alone variable attenuators to the output. Instead, an extra controllable polarization rotator is added in front of each output channel, before the two polarization states are recombined into a single beam by a polarizing beam splitter. If the extra controllable polarization rotator changes the direction of polarization by 90 degrees, then, when the light goes through the final polarizing beam splitter, it will be displaced to a different position than it would have been if its polarization hadn't been changed, and it will miss the output channel completely. If the extra controllable polarization rotator rotates the direction of polarization of the light by less than 90 degrees (in general it will make the light elliptically polarized in this case), then some of the light will change its polarization direction by 90 degrees, and some of it will remain in the original polarization state. Then, when the light goes through the final polarizing beam splitter, some of the light will recombine into a beam which is directed into the output channel, and some of it will be displaced by a different amount and will miss the output channel. By controlling the electric field on each of the controllable polarization rotators, the light going into each output channel can be attenuated by a controlled amount.

Another aspect of some embodiments of the invention concerns an optical switch in which unwanted paths are blocked, in order to reduce cross-talk. Cross-talk can occur between different channels if the polarizing beam splitter does not completely separate the two polarization states, or if the controllable polarization rotator, when it is supposed to be fully

active, does not convert an entering light beam into a completely orthogonal polarization state, but leaves a small component of the original polarization state. Cross-talk can also result from scattering of light. Any of these conditions will generally result in a small amount of light that was intended to go into one output channel ending up in the wrong output channel. In order to reduce cross-talk, additional controllable polarization rotators are placed in front of each output channel, before the polarizing beam splitter where the two beams of pure orthogonal polarization states recombine into one beam. Each of these additional controllable polarization rotators is set so that light that is supposed to enter that output channel is allowed through with no change in its polarization, while light that is not supposed to enter that output channel (i.e. cross-talk) has its polarization state converted to the orthogonal state (rotated 90 degrees, in the case of linearly polarized light) so that it cannot enter that output channel, but is displaced off to the side when it passes through the polarizing beam splitter.

Alternatively or additionally, polarizing filters, which let through light or one polarization and either absorb or scatter light of the orthogonal polarization, are placed anywhere in the optical path after the light has been directed toward one or the other output channel, and before the two beams going toward each output channel have been recombined into one beam. These polarizing filters are oriented so that they only let through light of the polarization that would be expected at that point, if all the polarizing beam splitters and controllable polarization rotators worked perfectly. Alternatively or additionally, controllable polarization rotators are placed anywhere in the optical path, even after the two beams going toward each output channel have been recombined into one beam, and polarizing filters are placed in the optical path after the controllable polarization rotators. These polarizers play the same role that the final polarizing beam splitters play, keeping light of the wrong polarization from going into the output channel. This configuration is useful if the final polarizing beam splitters are already being used for another purpose, such as variable optical attenuation (described below), so cannot also be used for blocking unwanted paths.

In some optical switching networks, unwanted paths are necessarily blocked, in order to make it possible to connect all the desired input channels to each output channel. This is true, for example, in the selector part of the router-selector optical switching network shown in Fig. 7. There is a controllable polarization rotator at the exit of each periscope (which functions as a beam combiner rather than a beam splitter) in the selector section of the network, where light from all the input channels going into a given output channel is repeatedly combined in a binary tree. The controllable polarization rotator must be active, rotating the polarization of light going through it by 90 degrees, whenever the light from the left side of one periscope

enters the right side of the periscope above it, or vice versa, in the schematic view in Fig. 7, and this automatically blocks the unwanted light from the other side of that lower periscope from entering that upper periscope. In other optical switching networks, blocking of unwanted paths is not a necessary part of the network, but is an optional added feature which improves performance by reducing cross-talk. That is true, for example, in the 2x2 switch shown in Fig. 6.

Blocking unwanted paths may increase the range of wavelengths that periscopes operate at, and may increase the tolerances for manufacture of periscopes. Thus two of the significant disadvantages of using periscopes as polarizing beam splitters may be at least partially overcome, and it becomes possible to take advantage of the desirable features of periscopes, such as their small size.

Another aspect of some embodiments of the invention concerns optical switches in which the parts of the switch are arranged in a three-dimensional configuration which is compact, easy to manufacture, or otherwise advantageous. One way to accomplish this is to use half-wave plates, with principle axes oriented at an oblique angle, before and after one or more of the controllable polarization rotators. This makes it possible to change the orientation of the principle axes of the controllable polarization rotator, in order to make the controllable polarization rotator fit better into the layout of the switch. In particular, if the controllable polarization rotator is a ferroelectric crystal, or a ceramic using the Kerr effect, then an electric field needs to be applied to it along one of the principle transverse axes, and a large uniform electric field is most readily applied if the controllable polarization rotator is short in that dimension, and has large, flat electrodes attached to its sides. (Similarly, if the controllable polarization rotator uses the Faraday effect, then a large uniform magnetic field is most readily applied if the controllable polarization rotator is short in the direction of the field.) If the polarizing beam splitter displaces the beam in a direction parallel to the direction of polarization of the displaced beam, then it is often most convenient to use a layout for the switch whose envelope has a rectangular cross-section, with principle axes parallel and perpendicular to the direction of polarization of the displaced beam. But the electric field in the controllable polarization rotator, in the case of a ferroelectric crystal or electro-optic ceramic, is at a 45 degree angle to the direction of polarization of the light that passes through it. By placing half-wave plates, oriented with their principle axis 22.5 degrees to the direction of beam displacement, before and after the controllable polarization rotator, the principle axes of the controllable polarization rotator can be aligned with the principle axes of the rectangular

cross-section of the envelope of the switch, and in particular the short dimension of the controllable polarization rotator can be aligned with the short dimension of the envelope.

Another aspect of some embodiments of the invention concerns all-optical switches with controllable polarization rotators using lead lanthanum zirconate titanate (PLZT), an electro-optic ceramic (using the Kerr effect) which has a response time of only 10 to 100 nanoseconds, much faster than the response time of ferroelectrics and nematic liquid crystals. However, the change in index of refraction in PLZT is proportional to the square of the electric field, in contrast to ferroelectrics where it is linear, and the effect is rather weak. Since operating at high voltage causes increased scattering of light, PLZT is often used at moderate voltages (20 to 80 volts), in which case a longer interaction length is needed (compared to ferroelectrics) to rotate the polarization by 90 degrees.

Another aspect of the invention concerns the ability to scale up a 1x2 or 2x2 optical switch to have many parallel input channels, each connected to its own one or two output channels. This can be done when the layout of the single 1x2 or 2x2 switch is essentially two-dimensional, for example the 1x2 switch design shown in Fig. 2 or the 2x2 switch shown in Fig. 6. Calcites, periscopes, and half-wave plates can simply be extended in a direction perpendicular to the plane of the drawing. Even controllable polarization rotators can be extended in this way if their electric field is in the plane of the paper, i.e. vertical in the case of a ferroelectric or an electro-optic ceramic, and horizontal (in the direction of propagation of the light) in the case of a twisted nematic liquid crystal. Then an arbitrary number of input and output channels can be lined up side by side.

There is thus provided, in accordance with an exemplary embodiment of the invention, an optical router-selector comprising:

at least four channels, including at least one input channel and at least one output channel;

a plurality of optical junction elements controllable to direct light from any input channel to any of the at least one output channels, wherein each element couples three optical paths, and comprises at least one controllable polarization rotator, the state of which determines whether and how much of light entering one of the paths exits through at least one of the other paths; and

a controller which controls the state of each controllable polarization rotator,

wherein the controller is configured to control all of the members of at least one set of two or more of the controllable polarization rotators to be in a same state at a given time.

In an embodiment of the invention, for at least one of the at least one sets, all of the controllable polarization rotators belonging to said set are comprised in junction elements that are splitters, configured so that light enters only one path and exits through either or both of the other paths.

Optionally, each of said splitters receive light from a same input channel, and not from any other input channel.

Optionally, no two members of said set are arranged in series along a same light path.

Optionally, said at least one sets whose members are comprised only by splitters, comprise a plurality of sets with no members in common, and no two members of any set in said plurality of sets are arranged in series along a same light path, and for all of the sets in said plurality of sets, the splitters receive light from a same input channel, and not from any other input channel.

In an embodiment of the invention, a router section originating at said input channel comprises a tree structure, within which tree structure all of the junction elements are splitters.

Optionally, all the splitters of said tree structure are arranged in N ordered router stages, such that no light path goes through more than one splitter in each router stage, and for any two positive integers i and j, where $i < j \leq N$, any light path that goes through splitters in both the ith router stage and the jth router stage goes through the splitter in the ith router stage before going through the splitter in jth router stage, and for each set in said plurality of sets, all the splitters are in a same router stage.

Optionally, within said tree structure, all the controllable polarization rotators comprised by each router stage which comprises more than one controllable polarization rotator, belong to a same set in said plurality of sets.

In an embodiment of the invention, every light path in said tree structure passes through a splitter belonging to each router stage, whereby the tree structure is a binary tree structure in which there are $2^{m-1}$ splitters at the mth router stage.

Optionally, for every input channel, a router section originating at that input channel comprises a binary tree structure, in which all the controllable polarization rotators comprised by the splitters at each router stage except the first router stage belong to a same one of the sets, and no two controllable polarization rotators comprised by the splitters at different router stages belong to a same one of the sets.

In an embodiment of the invention, for at least one of the at least one sets, all of the controllable polarization rotators belonging to said set are comprised by junction elements that

are joiners, configured so that light exits only one path and enters through either or both of the other paths.

Optionally, each of said joiners direct light toward a same output channel, and not toward any other output channel.

Optionally, said at least one sets whose members are comprised only by joiners comprise a plurality of sets with no members in common, and no two members of any set in said plurality of sets are arranged in series along a same light path, and for all of the sets in said plurality of sets, the joiners direct light toward a same output channel, and not toward any other output channel.

In an embodiment of the invention, a selector section terminating at said output channel comprises a tree structure, within which tree structure all of the junction elements are joiners.

Optionally, all the joiners of said tree structure are arranged in M ordered selector stages, such that no light path goes through more than one joiner in each selector stage, and for any two positive integers i and j, where $i < j \leq M$, any light path that goes through joiners in both the ith selector stage and the jth selector stage goes through the joiner in the ith selector stage after going through the joiner in jth selector stage, and for each set in said plurality of sets, all the joiners are in a same selector stage.

Optionally, within said tree structure, all the controllable polarization rotators comprised by each selector stage which comprises more than controllable polarization rotator, belong to a same set in said plurality of sets.

In an embodiment of the invention, every light path in said tree structure passes through a joiner belonging to each selector stage, whereby the tree structure is a binary tree structure in which there are $2^{m-1}$ joiners at the mth selector stage.

Optionally, for every output channel, a selector section terminating at that output channel comprises a binary tree structure, in which all the controllable polarization rotators comprised by the joiners at each selector stage except the first selector stage belong to a same one of the sets, and no two controllable polarization rotators comprised by joiners at different selector stages belong to a same one of the sets.

Optionally, any light path through which light exits from a splitter does not lead to a same output channel as the other light path through which light exits from said splitter.

Optionally, any light path through which light enters a joiner does not come from a same input channel as the other light path through which light enters said joiner.

In an embodiment of the invention, the number of input channels is equal to the number of output channels.

Optionally, at least one of the at least one sets of commonly controlled polarization rotators comprise a single controllable polarization rotator.

Optionally, each of the at least one sets of commonly controlled polarization rotators is comprised by a single controllable polarization rotator.

In an embodiment of the invention, a signal from at least one input channel is distributed to more than one output channel.

In an embodiment of the invention, at least one output channel obtains combined signals from two or more input channels.

Optionally, at least one controllable polarization rotator controls a degree of attenuation of at least one output channel.

Optionally, all the light paths from each input channel pass through a router section that comprises any splitters that said light paths pass through, before said light paths pass through any joiners.

Optionally, all the light paths going to each output channel pass through a selector section that comprises any joiners that said light paths pass through, after said light paths pass through any splitters.

In an embodiment of the invention, the light paths of each router section are co-planar, the light paths of each selector section are co-planar, the planes of all the router light paths are parallel to each other, the planes of all the selector light paths are parallel to each other, and the planes of all the router light paths are perpendicular to the planes of all the selector light paths.

Optionally, at least one of the junction elements comprises a polarizing beam splitter.

There is further provided, in accordance with an exemplary embodiment of the invention, an optical configuration, comprising:

a substrate;

at least a first optical element, with an optical axis, which element is coupled to said substrate;

a bearing comprising at least one joint formed between the first element and said substrate, such that the first element can be oriented on said bearing in a plurality of orientations; and

a curable adhesive in the joint, which, when said adhesive is cured, fixes an orientation of said joint.

Optionally, there is also a second optical element with an optical axis, which second element is coupled to the substrate, wherein the first element can be oriented on the bearing in

an orientation which brings the optical axis of the first element into substantial alignment with the optical axis of the second element.

Optionally, the first element can be moved on the bearing into a plurality of positions, in at least some of which positions the optical axis of the first element has a common orientation, and the first element can be moved on the bearing into a position and an orientation which brings the optical axis of the first element into substantial alignment with the optical axis of the second element.

In an embodiment of the invention, the bearing allows the first element to rotate about at least one axis and to slide along at least one axis.

Optionally, at least one of the at least one joints comprises a ball and socket joint.

Optionally, for at least some orientations of the first element the bearing allows the first element to rotate about at least one axis, and including a rotation limiter which limits the range of rotation of the first element about said axis when the first element is in at least some orientations.

Optionally, said rotation limiter is configured so that said range of rotation is adjustable.

There is further provided, in accordance with an exemplary embodiment of the invention, an optical configuration, comprising:

a substrate; and

at least a first optical element, with an optical axis, and including at least one convex surface and at least one concave surface, which element is coupled to said substrate;

wherein at least one of the at least one convex surfaces comprises a ball of a ball and socket joint, and at least one of the at least one concave surfaces comprises a socket of said ball and socket joint, such that the ball can be oriented relative to the socket in a plurality of orientations.

There is further provided, in accordance with an exemplary embodiment of the invention, an optical configuration, comprising:

a substrate;

at least a first optical element, with an optical axis;

a ball and socket joint coupling said first optical element to said substrate, the ball of which comprises a convex lens and the socket of which comprises a concave lens;

wherein the ball can be oriented relative to the socket in a plurality of orientations.

Optionally, there is also at least a second optical element coupled to the substrate, and the ball can be oriented relative to the socket so that the optical axis of the first element is substantially aligned with the optical axis of the second element.

Optionally, one or both of the ball and the socket are aspherical, and the asphericity limits the range of orientations of the ball relative to the socket.

Optionally, there is also a housing which keeps the ball from separating from the socket.

In an embodiment of the invention, there is also a curable adhesive in the ball and socket joint, which adhesive fixes an orientation of said ball and socket joint when said adhesive is cured.

Optionally, the curable adhesive is cured by ultraviolet light.

Optionally, one or more of said first element, said substrate and said bearing is transparent to ultraviolet light.

Alternatively or additionally, the curable adhesive is cured by heat.

Optionally, said adhesive is viscous and prevents slipping of said bearing when no external forces are applied to said first optical element.

In an embodiment of the invention, there is also at least one groove formed in the joint which is positioned such that excess amounts of the adhesive drain away from the joint via the groove.

Optionally, the at least one groove comprises two grooves.

Optionally, the two grooves are perpendicular to each other.

There is further provided in accordance with an exemplary embodiment of the invention, a polarizing beam-splitter apparatus, comprising:

an input port through which an input beam of light is provided;

a first polarizing beam splitter that receives the input beam and splits the beam into at least a first and second beam, said first beam having substantially a first desired polarization state and said second beam having a second polarization state orthogonal to said first polarization state but possibly admixed with the first polarization state; and

an optical system that receives the second beam and provides a third beam having the second polarization state and a smaller admixture of the second polarization state than the second beam. Optionally, the first beam splitter comprises a first planar surface that reflects light having the second polarization state and transmits light having the first polarization state and wherein the input beam is incident on the surface at a first angle. Optionally, the first angle is substantially 45$^{\circ}$.

In an exemplary embodiment of the invention, the optical system comprises a polarizing beam splitter that receives the second beam and splits the second beam into the third beam and a fourth beam having substantially the first polarization state. Alternatively or additionally, the optical system comprises a second beam splitter having a second planar surface that reflects light having the second polarization state and transmits light having the first polarization state and wherein the second beam is incident on the second planar surface at a second angle and light reflected by the second surface from the second beam forms the third beam and light transmitted by the second surface forms a fourth beam. Optionally, the apparatus comprises an absorber that receives the fourth beam. Alternatively or additionally, the second angle is substantially 45$^{o}$. Alternatively or additionally, the first and second surfaces are substantially parallel as a result of which, the first and third beams are parallel and displaced from each other. Alternatively or additionally, the first and second surfaces are surfaces formed on a same substrate material substantially transparent to light in the input beam.

In an exemplary embodiment of the invention, the apparatus comprises:

at least one controllable polarization rotator positioned to receive one of the first and third beams and operable to change the polarization state of the beam it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received beam responsive to the polarization state of the beam. Optionally, the at least one controllable polarization rotator comprises a polarization rotator for each of the first and second beams. Alternatively or additionally, the polarization rotator comprises:

at least one volume of PLZT through which light received by the rotator is transmitted; and

at least one electrode for applying a voltage to the volume of PLZT, which voltage controls the state to which the rotator changes the polarization of light that the rotator receives.

In an exemplary embodiment of the invention, the apparatus comprises a pair of polarization rotators arranged around said polarization controller, to rotate polarization of light entering and exiting said controller. Optionally, an electric field direction of said controller is perpendicular to a plane common to said beams.

There is also provided in accordance with an exemplary embodiment of the invention, a n optical switch comprising an input port through which the switch receives light and first and second output ports to which the switch selectively directs light that it receives comprising:

a first polarization state apparatus that receives light from the input port and provides a light beam having a desired polarization state;

a polarizing beam-splitter apparatus as described above that receives the light beam from the polarization state apparatus at the beam splitter apparatus input port and generates at least one first beam and/or at least one third beam responsive to the polarization of the light that it receives; and

wherein the first output port receives light from the at least one first beam and the second output port receives light from the at least one third beam. Optionally, the switch comprises:

a polarizing beam splitter that receives light from the input port and generates fifth and sixth spatially separated beams therefrom said fifth beam having substantially a third polarization state and said sixth beam having a fourth polarization state substantially orthogonal to the third state;

a second polarization state apparatus that receives the first and second beams of light and changes the polarization state of at least one of the fifth and sixth beams so that the polarization state of both beams is the same; and

wherein the fifth and sixth beams are directed to the input port of the beam splitter apparatus, which apparatus generates a first and/or third beam responsive to the fifth beam and a first and/or third beam responsive to the sixth beam. Optionally, the switch comprises a first polarizer through which light from the first beams from the polarizing beam-splitter apparatus is transmitted and wherein said first polarizer transmits substantially only light having the first polarization state. Alternatively or additionally, the switch comprises a second polarizer through which light from the third beams from the polarizing beam-splitter apparatus is transmitted and wherein said second polarizer transmits substantially only light having the second polarization state. Alternatively or additionally, the switch comprises:

a first optical combiner that combines light in the first beams provided by the beam splitter apparatus responsive to light in the fifth and sixth beams and directs the combined light to the first output port. Optionally, the switch comprises:

a second optical combiner that combines light in the third beams provided by the beam splitter apparatus responsive to light in the fifth and sixth beams and directs the combined light to the second output port.

In an exemplary embodiment of the invention, the first optical combiner comprises:

a third polarization state apparatus that receives the first beam provided from light in the fifth beam and transmits the light in the third polarization state and receives the light in the first beam provided by light from the sixth beam and transmits the light in the fourth polarization state;

an optical joiner that receives light in first beams from the third polarization state apparatus and combines the received light into a single beam that is transmitted to the first output port.

Alternatively or additionally, the second optical combiner comprises:

a fourth polarization state apparatus that receives the third beam provided from light in the fifth beam and transmits the light in the third polarization state and receives the light in the third beam provided by light from the sixth beam and transmits the light in the fourth polarization state;

an optical joiner that receives light in the third beams from the fourth polarization state apparatus and combines the received light into a single beam that is transmitted to the second output port.

In an exemplary embodiment of the invention, the switch comprises a first controllable attenuator controllable to attenuate light from the first combiner by a desired attenuation before the light reaches the first output port. Alternatively or additionally, the switch comprises a second controllable attenuator controllable to attenuate light from the second combiner by a desired attenuation before the light reaches the second output port.

In an exemplary embodiment of the invention, the first attenuator comprises:

at least one controllable polarization rotator positioned to receive the light from the first combiner and operable to change the polarization state of the light it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received responsive to the polarization state of the light.

In an exemplary embodiment of the invention, the second attenuator comprises:

at least one controllable polarization rotator positioned to receive the light from the second combiner and operable to change the polarization state of the light it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received responsive to the polarization state of the light.

In an exemplary embodiment of the invention, the polarization rotator comprises:

at least one volume of PLZT through which light received by the rotator is transmitted; and

at least one electrode for applying a voltage to the volume of PLZT, which voltage controls the state to which the rotator changes the polarization of light that the rotator receives.

There is also provided in accordance with an exemplary embodiment of the invention, a switch array comprising a plurality of switches as described herein, sharing an elongated optical element, said elongation being perpendicular to a plane of each of said switches.

In an exemplary embodiment of the invention, the switch comprises at least one reflector for folding an optical path of said switch.

There is also provided in accordance with an exemplary embodiment of the invention, a compound optical switch comprising at least two optical switches as described herein where the first output port of each optical switch is a same single first shared output port and the second output port of each optical switch is a same single second shared output port.

There is also provided in accordance with an exemplary embodiment of the invention, a compound optical switch comprising a cascade of optical switches wherein an n-th tier of the cascade comprises $2^n$ optical switches as described herein and where light from the first and second output ports of an optical switch in the n-th tier is input to the input ports of two optical switches in the (n+1)-st tier. Optionally, each optical switch in the n-th tier receives light from only a single output port of the optical switches in the (n-1)st tier. Alternatively or additionally, the switch comprises N tiers and comprising an output port that receives light from at least two output ports of the optical switches in the n-th tier.

There is also provided in accordance with an exemplary embodiment of the invention, a router-selector optical switching network, comprising:

a number of input channels equal to a power of two;

a number of output channels equal to the same or a different power of two;

a router section for each input channel comprising a binary branching tree of polarizing beam splitters, light paths joining them, and controllable polarization rotators;

a selector section for each output channel comprising a binary branching tree of polarizing beam joiners, light paths joining them, and controllable polarization rotators;

wherein the controllable polarization rotators operate to control the connection of any output channel to at most one input channel and any input channel to at most one output channel. Optionally, the light paths of each router are co-planar, the light paths of each selector are co-planar, the planes of all the router light paths are parallel to each other, the planes of all the selector light paths are parallel to each other, and the planes of all the router light paths are perpendicular to the planes of all the selector light paths. Alternatively or additionally, at least one of the polarizing beam splitters or one of the polarizing beam joiners is a polarizing beam splitter apparatus as described herein.

There is also provided in accordance with an exemplary embodiment of the invention, a method of aligning a first optical element with a second optical element comprising:

mounting the first optical element on a first part of a support comprising first and second parts, wherein the first part is movably coupled to the second part;

mounting the second part of the support in a fixed position relative to the second optical element;

applying a curable adhesive to the support so that the adhesive contacts both the first and second parts;

moving the first part so that the first optical element is aligned with the second optical element; and

curing the adhesive to secure the first part in the aligned position.

There is also provided in accordance with an exemplary embodiment of the invention, comprising:

a substrate;

at least two optical elements that lie in a same path and are coupled to said substrate; and

at least one ball and socket joint formed between at least one of said elements and said substrate, such that said one element can be oriented on said joint in a plurality of orientations relative to the other one of said elements. Optionally, the configuration comprises curable adhesive in the bearing. Optionally, the curable adhesive is cured by ultraviolet light.

In an exemplary embodiment of the invention, said adhesive is viscous and prevent slipping of said joint when no external forces are applied to said optical element. Alternatively or additionally, said one optical is transparent to ultraviolet light.

In an exemplary embodiment of the invention, said ball is on said substrate. Alternatively, said ball is on said element.

In an exemplary embodiment of the invention, said ball is integral to one of said substrate and said element. Alternatively, said ball is mounted on one of said substrate and said element. Optionally, said ball is attached using an adhesive to said one of said substrate and said element.

## BRIEF DESCRIPTION OF THE DRAWINGS

Exemplary embodiments of the invention are described in the following section with reference to the drawings. The drawings are generally not to scale.

Fig. 1 is a schematic side view of a periscope, according to an exemplary embodiment of the invention;

Fig. 2 is a schematic side view of a 1x2 switch, according to an exemplary embodiment of the invention;

Fig. 2A is a side view of the details of one end of the same switch near the output channels;

Fig. 3A is a schematic side view, and Fig. 3B is a schematic top view, of a 1x2 switch, according to another exemplary embodiment of the invention; Fig. 3C and Fig. 3D are schematic cross-sectional views of a 1x2 switch according to the same embodiment of the invention as shown in Fig. 3A and Fig. 3B, at different axial locations;

Fig. 3E is a schematic view of a 1x2 switch according to another exemplary embodiment of the invention;

Fig. 4 is a three-dimensional perspective view of a 2x2 switch, showing only the optical elements but not the mountings, according to an exemplary embodiment of the invention;

Fig. 5A is a schematic three-dimensional perspective view of a 2x2 switch, according to another exemplary embodiment of the invention; Fig. 5B is a schematic side view, and Fig. 5C is a schematic top view, of a 2x2 switch according to the same embodiment of the invention as Fig. 5A. Fig. 5D and Fig. 5E are schematic cross-sectional views of a 2x2 switch at different axial locations, according to the same embodiment of the invention as Fig. 5A;

Fig. 6 is a schematic side view of a 2x2 switch, according to another exemplary embodiment of the invention;

Fig. 7 is a schematic diagram of part of an optical implementation of a router-selector network with four input channels and four output channels, showing the topology of the network;

Fig. 8 is a schematic top view of the layout of the router part of a 4x4 optical router-selector network;

Fig. 9 schematically shows the entrance stage of a router-selector network using unpolarized light;

Fig. 10 is a perspective view of a 4x4 optical router-selector network;

Figs. 11A, 11B, 11C and 11D are schematic diagrams of bearings for aligning optical components;

Fig. 12 is a schematic drawing of an optical element in which the optical components themselves comprise a bearing; and

Fig. 13A is a side view of a ball and socket bearing, and Fig. 13B is a top view of the socket of the same bearing, showing grooves in the socket, according to an exemplary embodiment of the invention.

## DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 shows a periscope shaped component 200, according to an exemplary embodiment of the invention, which is used in some all-optical switches as a polarizing beam

splitter. A polarizing beam splitter splits a beam into two linearly polarized beams with orthogonal directions of polarization, for example horizontal and vertical, with the two beams traveling in the same direction with one beam displaced to the side, relative to the other beam. A light beam 202 enters periscope 200 at the lower left, and impinges on plate 204, which is mounted in the periscope at angle of 45 degrees to the direction of beam 202. The terms horizontal and vertical are used for clarity, the actual polarization directions are not generally required to be at any particular orientation relative to the perpendicular.

Plate 204 is coated with one or more optical coatings, whose thickness and index of refraction is such that they transmit one polarization and reflect the orthogonal polarization of light of the same wavelength as beam 202 which strikes it at a 45 degree angle. Light which is linearly polarized in a horizontal direction, for example, substantially passes through the plate without deflection, and emerges as a horizontally polarized beam 206, polarized in a direction perpendicular to the plane of the drawing. The part of the light in beam 202 which is polarized vertically is substantially all reflected, and travels upward as beam 208, with its polarization now in a left-right direction. Alternatively, depending on the characteristics of the optical coatings on plate 204, light which is linearly polarized in a horizontal direction is substantially all reflected from the plate, and light which is vertically polarized (i.e. polarized parallel to the plate) substantially all passes through plate 204. In the rest of this detailed description, this possibility will generally not be mentioned, since it is counter-intuitive. However, it should be understood that a polarizing beam splitter using optically coated plates may behave in this manner, in which case light beams emerging from a polarizing beam splitter may actually have polarization orthogonal to the direction that will be described.

It should be noted that a "reflective plate" may be implemented in various manners, for example by coating a surface of a glass element. For example, in many of the figures, the periscope is formed of a solid matrix, for example, bonded together plates, prisms and other optical elements. However, this is not essential and an open construction, with suitable spacers and scaffolding between the optical elements may be used instead.

Beam 208 then strikes plate 210, which is mounted parallel to plate 204, and is coated with the same kind of coating as plate 204, or another kind of coating which has the same property of reflecting or transmitting light according to its polarization, when light of the wavelength of beam 202 strikes it at a 45 degree angle. Because beam 208 is already largely linearly polarized in the left-right direction, most of it reflects from plate 210, and emerges from the periscope as a beam 212, which is linearly polarized in the vertical direction. To the extent that a small amount of beam 208 is polarized in a direction perpendicular to the plane of

the drawing, most of that component will emerge from the periscope vertically as a beam 214, which can be absorbed or otherwise discarded. As a result, beam 212 is even more in a pure state of linear polarization, in the plane of the drawing, than beam 208 is.

Optionally, beam 206 is made to pass through another coated plate (not shown in Fig. 1), oriented at the same angle as plate 204, or oriented perpendicular both to plate 204 and the plane of the drawing, so that any small component of vertically polarized light is deflected up or down, and beam 206 emerges with an even purer degree of horizontal linear polarization. Alternatively or additionally, beam 206 is made to pass through a polarizing plate which substantially removes vertically polarized light and passes horizontally polarized light.

A potential advantage of using a periscope as a polarizing beam splitter is that it is shorter in the direction of travel of the light, for the same beam displacement, than an alternative polarizing splitter, such as a crystal of calcite, or of another bifringent material such as yttrium vanadate. Potential disadvantages of the periscope include the need to accurately align the plates in three dimensions, and to accurately prepare the optical coatings, and the fact that the coatings are often designed to work only for a relatively narrow range of wavelengths, typically 100 angstroms or less, while calcite and similar materials typically have a wider wavelength operating range. Although ideally the plates do not absorb any light or scatter in it in other directions, in practical designs some of the light is absorbed or scattered, and the combined power of beams 206 and 212 is less than the power of beam 202. If a polarizer is put in the path of beams 206 and 212, oriented so as to transmit only the polarization that the beams are ideally supposed to have, then the periscope may work over a wider range of wavelengths, and may not have to be manufactured to as tight tolerances.

The actual angle at which plates 210 and 204 are mounted, nominally 45 degrees to the direction of propagation of beam 202, is not as important as the requirement that the plates be nearly parallel to each other. If the plates are mounted at a different angle than 45 degrees, but still parallel to each other, then beam 208 will not be vertical, but will travel at an angle to the vertical. But this will not affect the operation of the periscope as long as beam 208 hits plate 210 and beam 212 exits from the periscope along the proper path. If plate 204 is not parallel to plate 210, then beam 212 will not emerge parallel to beams 206 and 202, and the operation of the device may be more seriously affected. In particular, it will not be possible to align the paths of both beams if the rest of the switch is designed assuming that the paths of the beams are parallel, and even if the design takes the possibility of non-parallel beams into account, it will take more effort to align all the optics.

Fig. 2 shows a 1x2 all-optical switch 300, according to an embodiment of the invention. In switch 300, there is an input beam of light 302, which is conveyed to either of two output channels 330A or 330B. Input beam 302, which is, for example, traveling along a fiber optic cable, is collimated to enter a calcite crystal 310. Collimation is accomplished by a ferrule 304 and a gradient-index lens 306, or by any other means known to the art. Optionally, another type of bifringent crystal, for example a synthetic crystal such as yttrium vanadate, is used instead of calcite. Optionally, any other type of polarizing beam splitter is used instead of calcite, including a periscope such as that shown in Fig. 1. Optionally, calcite 310 is mounted on a bearing 311, for example a ball and socket bearing, which allows it three degrees of rotational freedom, in order to align it with the input beam 302 which is entering it, and in order to align the beams exiting it with the optical elements to the right of it in Fig. 2. Optionally, bearing 311 also has one or more translational degrees of freedom, for example, including steps, or being elongated or otherwise distorted in a certain direction. In an exemplary embodiment of the invention, the socket is an elongate socket in a direction of translational freedom. Optionally, bearing 311 has only one or two rotational degrees of freedom. Calcite 310 is rotated and/or translated on bearing 311, with beam 302 turned on, until it is aligned correctly. The correct alignment is determined, for example, by observing the two beams exiting calcite 310, and seeing that they impinge at the proper place on the next element, or any other means of alignment is used. Once calcite 310 is correctly aligned, bearing 311 is optionally fixed in place. For example, bearing 311 contains an uncured UV cured adhesive, and once calcite 310 is aligned, ultraviolet light is used to cure the adhesive.

Calcite 310 is oriented so that the two beams emerging from it are polarized at angles of 45 degrees in opposite directions from the vertical. The upper beam passes through half-wave plate 312A, and the lower beam passes through half-wave plate 312B. Half-wave plates 312A and 312B are made of a birefringent material, in which the index of refraction for light polarized along one principal axis is different from the index of refraction of light polarized along the other principal axis. The thickness of plates 312A and 312B is such that, for light of the wavelength in beam 302, light polarized along one principle axis will have half a wavelength more across the thickness of the plate than light polarized along the other principal axis. Plate 312A has a principle axis oriented at 22.5 degrees on one side of the vertical, and plate 312B has a principle axis oriented at 22.5 degrees on the other side of the vertical. The beam passing through plate 312A is polarized 45 degrees from the vertical, on the same side of the vertical as the principal axis of plate 312A, while the beam passing through plate 312B is

polarized 45 degrees from the vertical, on the same side of the vertical as the principle axis of plate 312B. Thus, both beams emerge from their plates with vertical polarization.

The two vertically polarized beams emerging from plates 312A and 312B enter a controllable polarization rotator 314. The controllable polarization rotator is optionally made of a ceramic electro-optic material, such as lead lanthanum zirconate titanate (PLZT, for example $Pb_xLa_{(1-x)}(Zr_yTi_z)(1-x/4)$ (x=9 or 8.5, y=65, z=35)), which has index of refraction that differs for light polarized in the direction of an applied electric field, and light polarized transverse to that direction. If an electric field is applied at an angle of 45 degrees to the vertical, of magnitude such that the difference in the two indexes of refraction will lead to a difference in half a wavelength (or any odd number of half wavelengths) for light propagating across the length of the PLZT, then light that is initially polarized vertically will emerge with its polarization horizontal, and vice versa. If no electric field is applied to the PZLT, then the light will emerge with the same polarization as it started with.

Alternatively, a material which exhibits an magneto-optic effect (e.g., Faraday rotation) can be used instead of the PLZT. Here the beam is parallel to magnetic field lines. In order to reduce the cross talk resulted from non-accurate rotation of the polarization the temperature of the faraday rotator is optionally kept at the optimal temperature of the rotator which is used.

Alternatively, other materials which respond according to the Kerr or the Pockels effect can be used. Also, a ferroelectric crystal such as lithium niobate, or a ferroelectric liquid crystal, can be used for the controllable polarization rotator. Such materials work similarly to electro-optic ceramics, but have slower response time, and do not require as high an electric field. Alternatively, nematic liquid crystals, twisted or untwisted, can be used. In the case of twisted nematic liquid crystals, the electric field is applied along the direction of propagation of the light, and makes the material not affect polarization. When no electric field is applied, a linearly polarized beam of light has its direction of polarization rotate as it propagates through the material. Such liquid crystals have even slower response time than ferroelectrics.

When the two beams of light enter controllable polarization rotator 314 with vertical polarization, if rotator 314 is inactive (e.g., does not provide rotation, even if, for some materials, an electric field is present), the beams emerge with polarization vertical, and when they enter a periscope 316, they are reflected off the two plates in the periscope and exit the periscope at the top. If controllable polarization rotator 314 is active, then the two beams of light emerge with horizontal polarization (in a direction perpendicular to the plane of the drawing), and they go straight through periscope 316, emerging at the bottom of periscope 316. In the first case, the beams will end up at an output channel 330A, at the upper right of Fig. 2,

while in the second case, the beams will end up at an output channel 330B, at the lower right of Fig. 2. The state of polarization rotator 314, whether it is active or inactive, thus determines which output channel the light will end up at.

There are other ways of configuring calcite 310, half-wave plates 312A and 312B, and controllable polarization rotator 314, which will result in the beams entering periscope 316 selectively having either horizontal or vertical polarization. For example, calcite 310 is oriented so that the two beams emerging from it are polarized vertically and horizontally, and the horizontally polarized beam passes through a half-wave plate, say 312A, which is oriented with its principle axes at a 45 degree angle to the vertical, while the vertically polarized beam goes straight to controllable polarization rotator 314, without passing through a half-wave plate at all. Then both beams are vertically polarized when they reach controllable polarization rotator 314. Alternatively, only the vertically polarized beam passes through a half-wave plate, and both beams arrive at controllable polarization rotator 314 with horizontal polarization. Optionally, controllable polarization rotator 314 is oriented with its principle axis at an angle other than 45 degrees, and an additional half-wave plate, between controllable polarization rotator 314 and periscope 316, rotates the direction of polarization of light emerging from controllable polarization rotator 314 so that it is polarized vertically or horizontally when it enters periscope 316. There are many other configurations which will be obvious to someone skilled in the art.

Optionally, periscope 316 is replaced by a calcite, oriented in such a way as to separate light polarized vertically from light polarized horizontally. However, a calcite will have to be much longer than periscope 316 to obtain the same spatial separation between light going into different output channels.

Optionally, light emerging from periscope 316 passes through a polarizer 317A if it emerges at the top, and/or a polarizer 317B if it emerges at the bottom. These polarizers either absorb or scatter most light of the wrong polarization, and pass most of the light of the polarization that is supposed to emerge from that part of periscope 316, viz. vertical polarization at the bottom, and horizontal polarization at the top. The polarizers thus reduce cross-talk, the phenomenon of some light entering the wrong output channel because, for example, controllable polarization rotator 314 does not accurately rotate the polarization of light traversing it and/or periscope 316 does not perfectly separate light of vertical polarization from light of horizontal polarization. Optionally, there is only one polarizer, 317B, in front of the bottom of periscope 316, because light emerging from the top of periscope 316 has already been reflected from two polarizing plates inside periscope 316, and is more purely polarized in

the right direction than light emerging from the bottom of periscope 316, which has only passed through one polarizing plate.

Each of the two beams then passes through one of the four half-wave plates 320A, 320B, 320C, or 320D, which restores its original polarization direction. If the beams emerge from the top of periscope 316, then they pass respectively through half-wave plates 320A and 320B. The orientation of plates 320 is related to the orientation of half-wave plates 312A and 312B. For example, if the beams emerge from half-wave plates 312A and 312B with vertical polarization, as they do in the original configuration described above, then, if controllable polarization rotator 314 is inactive, the beams will exit periscope 316 at the top also with vertical polarization. Half-wave plates 320A and 320B then have the same orientation of their principle axes as half-wave plates 312A and 312B, and the beams emerge from half-wave plates 320A and 3120B with the same directions of polarization as they had when they left calcite 310.

The beams then enter a calcite 322A, which is oriented in such a way as to recombine the two beams into a single beam, with the same polarization state (including possibly an unpolarized state) as the light which entered calcite 310. If controllable polarization rotator 314 is active, then the beams will emerge from the lower part of periscope 316, instead of from the upper part, and they will have horizontal polarization instead of vertical polarization. In order to restore the polarization of the beams to the original polarization that they had when emerging from calcite 310, half-wave plates 312C and 312D have principle axes oriented 22.5 degrees and 67.5 degrees from the vertical. The beams then enter calcite 322B, which is oriented in such a way as to recombine the two beams into a single beam, with the same polarization state as the beam which entered calcite 310.

Optionally, in order to further reduce cross-talk, there are two controllable polarization rotators 318A and 318B together with, respectively, caclites 322A and 322B, one for light emerging from the top part of periscope 316 and one for light emerging from the bottom part of periscope 316. If the light is being directed into output channel 330A, then most of the light emerges from the upper part of periscope 316, but due to imperfections in the performance and orientation of the optical elements, some light emerges from the bottom part of periscope 316. To keep this light out of output channel 330B, particularly if polarizers 317A and 317B are not used, controllable polarization rotator 318B is active, rotating the polarization direction by 90 degrees. When this light enters calcite 322B, it will not have the proper polarization to be recombined into a single beam that is aligned to enter output channel 330B, but will instead be displaced to the side, where optionally it is absorbed, to prevent some of it from eventually

entering output channel 330B after further scattering. Controllable polarization rotator 318A, on the other hand, is inactive, so the light entering calcite 322A is polarized in the proper direction to recombine into a single beam, and enter output channel 330A.

Many other configurations are possible, and will occur to persons of the art, which accomplish the same result, with minor structural variations, using the same inventive concept. For example, controllable polarization rotator 318B is active when the light is supposed to go into output channel 330B, and inactive when the light is supposed to go into output channel 330A, and half-wave plates 320C and 320D have the same orientation of their principle axes as half-wave plates 312A and 312B. Then, when the light is supposed to go into output channel 330B, controllable polarization rotator 318B changes the polarization of the light emerging from the lower part of periscope 316 from horizontal to vertical, and half-wave plates 320C and 320D restore the polarization of the beams entering calcite 322B to the same polarization as the beams had when they emerged from calcite 310, so that calcite 322B can recombine them into a single beam. Many other possible configurations will be obvious to someone skilled in the art.

Calcites 322A and 322B are optionally mounted on bearings 323A and 323B, which are used to align them, as described above for calcite 310. Light emerging from calcite 322A enters a gradient-index lens 326A which focuses it on a fiber optic cable (optionally held by a ferrule 328A) which constitutes output channel 330A. A similar gradient-index lens 326B and ferrule 328B are used to bring light emerging from calcite 322B into output channel 330B.

If an electric field is applied to controllable polarization rotator 314 which is less than the electric field needed to make it rotate the polarization by 90 degrees, then vertically polarized light entering it will emerge with an elliptical polarization that is a combination of vertical and horizontal polarization. As a result, some of the light will end up in output channel 330A and some of it will end up in output channel 330B, with the relative amount of light in the two channels depending on the electric field applied to controllable polarization rotator 314. In this mode, the switch operates as a multicaster, distributing an input signal to two (or more) output channels. In this mode of operation, neither controllable polarization rotator 318A or 318B is active, since some light is supposed to end up in both channels. If one of the output channels is terminated by a material which absorbs light, or the light is otherwise discarded, then the multicaster becomes a variable attenuator, in which the amplitude of light in the one remaining output channel is reduced from its value in the input channel, by an amount that depends on the electric field applied to controllable polarization rotator 314. Variable attenuation in the output can also be achieved, even when the switch or multicaster is operating

with two output channels, by changing the electric field in controllable polarization rotators 318A and 318B. If these are operated at an electric field less than that needed to make them rotate the polarization direction by 90 degrees, then the light going into the corresponding output channel 330A or 330B will be reduced in power from what it would be if controllable polarization rotators 318A and 318B were not operating at all, but the light will not be eliminated from that channel completely. The switch may also be hardwired (e.g., by omitting or replacing elements) and/or permanently electrically controlled to be a variable attenuator and/or multicaster.

Fig. 2A shows some details of how the light emerging from calcites 322A and 322B is fed into fiber optic cables 328A and 328B, according to an exemplary embodiment of the invention. This configuration, in which the upper and lower light beams cross each other, is one possible way of implementing the optical paths from calcites 322A and 322B to output channels 330A and 330B, which are shown schematically in Fig. 2. A similar configuration is also optionally used for the path from input channel 302 to calcite 310 in Fig. 2, and for the input and/or output channels in the optical switches and switching networks shown in any of the other drawings, when calcites are used for polarizing beam splitters. The optical paths shown in Fig. 2A are not necessarily drawn to scale. In particular, it should be noted that the angles of the oblique light beams are generally not the same inside the calcites, between the calcites and the gradient index lens 326, and inside the gradient index lens, although they are drawn all at the same angle. The angle of orientation of the faces of the calcites 322A and 322B is chosen so that the beams of both polarizations emerging from each calcite will leave the calcite superimposed and travelling in the same direction, and will be focused on the proper fiber optic cable once they have passed through the gradient index lens. This face angle, the positions of the calcites and the fiber optic cables, and the dimensions of the lens, are related to each other and to the index of refraction and degree of birefringence of the calcite, and the index of refraction of the lens, and are not necessarily drawn to scale in Fig. 2A.

In an exemplary embodiment of the invention, the switch (e.g., Figs, 2 and 6) can be scaled, for example by arranging an array of N 1X2 switches side by side. In an exemplary embodiment of the invention, this is done by elongated some of the optical elements (e.g., calcite 310, periscope 316 and calcites 322) in a direction perpendicular to the page, with the multiple input and output channels optionally being arranged in the same direction. Alternatively, for example in order to facilitate the alignment either the $YVO_4$ 200 or $YVO_4$ 220 or $YVO_4$ 204 can be replaced by a set of N smaller $YVO_4$ similar to 310 of Fig. 2. In an exemplary embodiment of the invention, the switch manufactured by assembly. Alternatively

lithography or other on-substrate forming methods are used. The final switch may be discretely packaged component or may be part of a network or an array of switches, for example as described elsewhere in this application. Both small- and large- sized optical switches may be manufactured, for example in the in, cm, mm or sub mm size ranges.

Fig. 3 shows a 1x2 switch 10 according to another exemplary embodiment of the invention. It differs from the 1x2 switch shown in Fig. 2 primarily in that it uses periscopes rather than calcites for the initial separation of the input light into two orthogonally polarized beams, and for recombining the two beams into one beam before the light enters the output channel. This makes the switch in Fig. 3 shorter than the switch in Fig. 2, and/or it makes the separation between the two beams greater in the switch in Fig. 3 than in the switch in Fig. 2. The increased separation between the two beams in the switch in Fig. 3 makes it more practical than in Fig. 2 to send each of the two beams to separate controllable polarization rotators, and for this reason the function of some of the half-wave plates in Fig. 2 can be accomplished by controllable polarization rotators in Fig. 3, and fewer half-wave plates are needed for the switch in Fig. 3. Some disadvantages of the switch in Fig. 3 compared to the switch in Fig. 2 are that the periscopes all require precise alignment of the plates, and precise manufacture of the coatings on the plates, and the periscopes may lose more light than the calcites.

Fig. 3A shows a side view of switch 10, and Fig. 3B shows a top view. Light from an input channel 2 enters a periscope 4, where it is split into two beams. The component of the input light with vertical polarization passes straight through periscope 4, while the component with horizontal polarization is displaced to the right. The vertically polarized beam passes through a controllable polarization rotator 8A, and the horizontally polarized beam passes through a controllable polarization rotator 8B. Controllable polarization rotators 8A and 8B each change vertically polarized light to horizontal polarization, and vice versa, when they are active, and do not change the polarization of light entering them when they are inactive. Optionally, they are made of PLZT. Alternatively, they are made of any of the other materials discussed above in describing controllable polarization rotator 314 in Fig. 2. If controllable polarization rotator 8A is active and controllable polarization rotator 8B is inactive, then the light emerging from both controllable polarization rotators is horizontally polarized. If controllable polarization rotator 8A is inactive and controllable polarization rotator 8B is active, then the light emerging from both controllable polarization rotators is vertically polarized. The light emerging from both controllable polarization rotators enters the lower part of a periscope 12. If the light entering periscope 12 is vertically polarized, then it reflects off both plates 12A and 12B in periscope 12, and emerges from the upper part of periscope 12. If

the light entering periscope 12 is horizontally polarized, then it passes through plate 12A and emerges from the lower part of periscope 12. The light emerging from the upper part of periscope 12 ultimately ends up in an output channel 22, while the light emerging from the lower part of periscope 12 ultimately ends up in an output channel 24.

Optionally, to reduce the amount of light going into the wrong channel due, for example, to less than perfect manufacturing of periscope 12 and/or inaccuracy in the operation of controllable polarization rotators 8A or 8B, polarizing plates 18A and 18B are inserted after periscope 12, as described above with respect to polarizers 317A and 317B of Fig. 2. These plates pass only light of the polarization that is supposed to be emerging from the upper and lower parts of periscope 12, and either absorb or scatter light of the wrong polarization. Fig. 3D shows polarizing plates 18A and 18B from an axial point of view.

The two beams emerging from periscope 12 pass through an element $16A_1$ on the left and an element $16A_2$ on the right (Fig. 3C), if they emerge from the top of periscope 12. If the two beams emerge from the bottom of periscope 12, then they pass through an element $16B_1$ on the left and an element $16B_2$ on the right. Optionally, these four elements are mounted on a matrix 16, a shown in Fig. 3C, which is a cross-sectional view of the switch, at the location labeled C—C′ in Fig. 3B. Elements $16A_2$ and $16B_1$ are clear glass or open holes which do not affect the polarization of the light at all, and elements $16A_1$ and $16B_2$ are half-wave plates which change the polarization of light passing through them from horizontal to vertical, and vice versa. Then, the beam emerging from the left side of matrix 16, whether on the top or the bottom, is horizontally polarized, and light emerging from the right side of matrix 16, whether on the top or the bottom, is vertically polarized. The light emerging from matrix 16 enters a periscope 20. The light entering periscope 20 the left side, because it is horizontally polarized, is reflected from plates 20B and 20A, and emerges from periscope 20 on the right side, while the light entering periscope 20 on the right side, because it is vertically polarized, passes through plate 20A and combines with the light entering periscope 20 on the left side to form a single beam, with the same polarization state (including possibly unpolarized) as the input beam. The emerging single beam goes into output channel 22 if it went through the upper parts of matrix 16 and periscope 20, and it goes into the output channel 24 if it went through the lower parts of matrix 16 and periscope 20. It should be appreciated that if polarization preservation is not required, several elements of the above embodiment may be omitted, for example, beam combiner 20B can be a simple mirror.

Alternatively, in order to reduce the amount of light going into the wrong channel, the elements in matrix 16 are all controllable polarization rotators. If the light is supposed to go

into output channel 22, then the elements on the left side of matrix 16 are active and change the polarization direction from horizontal to vertical and vice versa, while elements on the right side of matrix 16 are inactive and do not change the polarization of light passing through them. If the light is supposed to go into channel 24, then the elements on the right side of matrix 16 are active and the elements on the left side of matrix 16 are inactive. Then, light that is headed for the wrong channel will enter periscope 20 with the wrong polarization, and it will not emerge from periscope 20 as a single beam headed for one of the output channels, but will either pass through plate 20B and miss the output channel, or it will reflect from plate 20A and be deflected off to the right, again missing the output channel. Optionally, this light is absorbed in a black material, to minimize stray light entering the output channels.

Optionally, controllable polarization rotators 8A and 8B are operated at intermediate values of electric field, so that the switch operates as a multicaster, as described above for the switch in Fig. 2. Also similarly to the switch in Fig. 2, the switch in Fig. 3 optionally operates as a single output variable attenuator, by blocking one of the outputs. Alternatively it operates as a two-output switch or multicaster with variable attenuation, by using the controllable polarization rotators in matrix 16 to affect the amount of light reaching each output channel, as described for the switch in Fig. 2.

Various other configurations of the switch in Fig. 2 will be obvious to a person skilled in the art, without departing from the teaching of the invention. For example, instead of making the polarization of the two beams the same after the input beam is split into two orthogonally polarized beams, the polarization of the two beams can be kept orthogonal to each other, and the two beams can be made to pass through a single controllable polarization rotator and then through two different periscopes, in order to direct each beam to the proper output channel, before recombining them into one beam. This is more practical if the initial splitting and final recombining of the beam is done with periscopes, rather than with calcites as in Fig. 2, since the beams can be further apart if periscopes are used.

Both the switch shown in Fig. 2 and the switch shown in Fig. 3 can be used as 2x1 switches, with two input channels and one output channel, rather than as 1x2 switches, simply by reversing the input and output channels. Then, by making the controllable polarization rotators (314 in Fig. 2, or 8A and 8B in Fig. 3) either active or inactive, the signal from either input channel can be directed to the output channel. By using intermediate values of electric field in the controllable polarization rotators, any desired combination of the two input signals can be directed to the output channel.

Fig. 3E shows a 1x2 compact switch, which may be useful, for example, to reduce the foot print of a switch, in accordance with an exemplary embodiment of the invention. The input light 370 is conveyed by e.g. collimation means,(as described before) into a $YVO_4$ crystal 372; the emerging beams (S and P polarizations) pass via half wave plates 374A and B (optionally rotated like 312A and 312B of Fig. 2) and a controllable polarization rotator 376. The latter selects the output port for the beams.

In an exemplary embodiment of the invention, a compact footprint is provided by folding the optical paths. In one example, the beams are reflected by a reflector 378 (e.g., total reflection), and according to their polarization state are either reflected or refracted by a polarizing beam splitter 380. The angle between surface 378 and 380 is, for example, 90 degrees. A surface 382 which is optionally also totally reflecting is used to collect the refracted light. If the beams are reflected by splitter 380 they pass through a rotating polarization rotator 384 which together with calcite 388 removes unwanted crosstalk, using a half wave plates 386 as described above. The beams emerge through output channel 390. If the beams are refracted by splitter 380 they are reflected by reflector 382 and exit via an output channel 392 in a similar way to channel 390. It should be noted that this structure may be formed as a stack with the channels one above another, for example, to allow an elongate array of switches to be provided.

Fig. 4 shows a 2x2 switch, in accordance with an embodiment of the invention. There are two input channels, 600A and 600B, which are directed to two output channels, 626A and 626B. Each input beam passes through a calcite 604, which splits it into two orthogonally polarized beams, polarized at angles of +45 degrees and –45 degrees to the vertical. The four beams each pass through one of the four half-wave plates 606(A,B) and 607(A,B), which rotate their polarization direction by +45 degrees or –45 degrees so that they all emerge polarized in the vertical direction. All four beams then pass through controllable polarization rotators 608(A,B). Optionally there is only one controllable polarization rotator 608, wide enough so that all four beams pass through it. In an exemplary embodiment of the invention, the orientation of polarization rotator(s) 608 is selected to be at 45 degrees to the vertical, so that application of a similarly oriented electric field is facilitated.

If controllable polarization rotators 608 are not active, then the light remains vertically polarized. The light from input channel 600A passes through a plate $610A_1$ in a periscope 610A, and is then reflected from plates 612A and 612B in a periscope 612, and eventually reaches output channel 626A. Light from input channel 600B passes straight through a periscope 610B, and then through a half-wave plate 611B, which changes its polarization from

vertical to horizontal. It then passes straight through periscope 612B, eventually reaching output channel 626B.

If controllable polarization rotators 608 are active, then the light emerges from them polarized horizontally. Light from input channel 600A is displaced to the left by periscope 610A, and passes through a half-wave plate 611A, which makes its polarization vertical. Periscope 612 then displaces the light upward, and it emerges from periscope 612 aimed at output channel 626B, which it eventually goes into. Similarly, light from input channel 600B eventually ends up at output channel 600A. In summary, light from each input channel goes into the corresponding output channel, 600A into 626A and 600B into 626B, if controllable polarization rotators 608 are inactive, while the light from the two input channels switches places, 600A into 626B and 600B into 626A, if controllable polarization rotators 608 are active.

Optionally there are controllable polarization rotators 614A and 614B together with polarizers 622A and 622B, which serve to reduce cross-talk, keeping light of the wrong polarization (and hence from the wrong input channel) out of each output channel. For example, in one possible configuration of the switch, controllable polarization rotators 614A and 614B are active if and only if controllable polarization rotators 608 are. Then regardless of whether the input channels are switched (600A going into 626B and 600B going into 626A) or not, light from the proper channel will be horizontally polarized in front of polarizer 622B, and vertically polarized in front of polarizer 622A, while light from the wrong channel will have polarization orthogonal to those directions. Polarizer 622A blocks horizontally polarized light and polarizer 622B blocks vertically polarized light, so cross-talk is reduced.

In the configuration just described, the rule for controlling the switch is that all four controllable polarization rotators 608 and 614 are active if the channels are to be switched, and none of the controllable polarization rotators are active is the channels are not to be switched. But other sets of rules will also work, provided that the eight half-wave plates 606, 607, 616, and 617 have corresponding orientations of their principle axes. For example, the rule could be that rotators 608 are active, and rotators 614 are inactive, in order to switch channels. Or, the rule could be that 608A is active, while 608B, 614A, and 614B are inactive, in order to switch channels.

Optionally, there are controllable polarization rotators 624A and 624B, which, together with calcites 618A and 618B, serve as variable attenuators for each output channel. By changing the polarization state away from the polarization, pure horizontal or pure vertical, which is designed to go through each output channel, controllable polarization rotators 624A

and 624B can reduce the amount of light that enters each channel. If light of the wrong polarization enters calcite 618A or 618B, the beams will not recombine and enter the output channels 626A or 626B, but will be displaced to the side.

By operating controllable polarization rotators 608 at intermediate values of electric field, the switch can act like a variable adder, putting any desired linear combination of the two input channels into one output channel, and the remaining power from each input channel into the other output channel.

Optionally, input channel 600B, and the associated calcite 604B, half-wave plates 607 and controllable polarization rotator 608B, are directly above input channel 600A, instead of being above and to the left of it. Then periscope 610B is changed so that it displaces a beam to the left instead of to the right, and the rule for when the controllable polarization controllers are active is changed, or else the directions of orientation of the principle axes of the half-wave plates 607 are changed. The resulting configuration resembles Fig. 5.

Fig. 5 shows a 2x2 switch 100 according to another exemplary embodiment of the invention. Like the 1x2 switch shown in Fig. 3, the 2x2 switch shown in Fig. 5 differs from the 2x2 switch shown in Fig. 4 primarily in using periscopes instead of calcites for the initial splitting of the beam into two beams of orthogonal polarizations, and for the final recombining of the two beams into a single beam. The advantages and disadvantages of the configuration shown in Fig. 5 are similar to those described for Fig. 3. Optionally, an optical blocker or absorber is provided between stacked periscopes, for example to reduce cross-talk. Fig. 5A shows a three-dimensional perspective view of switch 100, Fig. 5B shows a side view, and Fig. 5C shows a top view. Light from input channels 102A and 102B passes through a periscope 110, which is really two periscopes one stacked on top of the other, and the light from each channel is divided into two beams, polarized vertically and horizontally. Controllable polarization rotators 120 make the polarization of both beams from a given input the same, and make the polarization vertical for the beams which are going to end up at an output channel 170, and horizontal for the beams which are going to end up at an output channel 180. A periscope 130 then displaces the beams to the left if they are supposed to go to output channel 180, and keeps them on the right if they are supposed to go to output channel 180. Half-wave plates 125A and 125B, shown in Fig. 5D which is a cross-sectional view (and indicated as 125 in Figs. 5A and 5B), change the polarization of some of the beams, so that all beams end up at the upper part of a periscope 140, regardless of which output channel they are going to. Finally, controllable polarization rotators 150, shown in a cross-sectional view in Fig. 5E, restore the beams whose polarization was changed to the polarization they had when they emerged from

periscope 110. A periscope 160 recombines each pair of beams from the same input channel into one combined beam again, which goes out output channel 170 or 180, depending on whether that combined beam is on the left side or the right side of the switch.

Variable attenuation and mixing can be achieved in switch 100 by using intermediate values of electric field in controllable polarization rotators 150 and 120 respectively, similar to the switch in Fig. 4.

Fig. 6 is a 2x2 switch according to another exemplary embodiment of the invention. This switch uses calcites not only for separating beams initially into orthogonal polarized components, like the switches in Fig. 2 and Fig. 4, but even uses calcites for displacing beams according to which output channel they are going into, a function performed by a periscope in other embodiments. While this makes the switch in Fig. 6 longer than the other switches, there are no periscopes to manufacture, and the calcites can be used over a much broader range of wavelengths than a typical periscope can, with its precise optical coatings and angles. Furthermore, the layout of the switch shown in Fig. 6, unlike those in Fig. 4 and Fig. 5, is largely confined to the plane of the drawing, and can have rather small width in the direction perpendicular to the plane of the drawing. This allows many such switches to be stacked up in parallel in a relatively small space.

Light beams from two input channels 802A and 802B each enter a calcite 800A or 800B, where they are separated into beams polarized vertically and horizontally. Each of the resulting four beams passes through a different half-wave plate 804, which are oriented in such a way that all four beams emerge with the same polarization direction, 45 degrees from the vertical. (The half-wave plates are oriented with their principle axes either 22.5 degrees or 67.5 degrees from the vertical.) The beams then pass through a controllable polarization rotator 806, which has its electric field oriented horizontally, perpendicular to the plane of the drawing. The horizontal orientation of the electric field allows controllable polarization rotator 806 to be made very narrow in the direction of the electric field, with broad flat electrodes mounted on each side of it, producing a uniform field, and not requiring a very high voltage to obtain a high electric field.

Light passing through controllable polarization rotator 806 has its polarization changed by 90 degrees, from +45 degrees to –45 degrees or vice versa, when controllable polarization rotator is active, with an electric field of the right magnitude. When it is inactive, with no electric field, the polarization of light passing through it remains the same. The light then passes through a half-wave plate 807, with principle axes oriented in such a way (either 22.5 or 67.5 degrees from the vertical) so that the light emerging from controllable polarization

controller 806 is all rotated by 90 degrees, and hence has either horizontal or vertical polarization. The four beams then enter a calcite 808, where the beams that are vertically polarized are deflected downward, while the beams that are horizontally polarized pass straight through. Light entering calcite 808 which came from input channel 802B goes to location 808C if it is not deflected, and goes to location 808B if it is deflected. Light entering calcite 808 which came from input channel 802A goes to location 808B if it is not deflected, and goes to location 808A if it is deflected. There is a half-wave plate 809 at location 808B, which rotates the polarization of light passing through it by 90 degrees, changing horizontal to vertical polarization and vice versa. The light then passes through a calcite 810, where it goes straight through if it is polarized horizontally, and is deflected upward if it is polarized vertically.

In order to send the signal from each input channel to the corresponding output channel, i.e. to send input channel 802A to an output channel 820A, and to send input channel 802B to an output channel 820B, the light from input channel 802B arrives at calcite 808 with horizontal polarization, and the light from input channel 802A arrives at calcite 808 with vertical polarization. Then the light from input channel 802B goes to location 808C and from there, through calcite 810, to output channel 820B. Light from input channel 802A is deflected down to location 808A, and then deflected back up through calcite 810 to output channel 820A. All four light beams miss half-wave plate 809, so they have the same polarization in calcite 810 as they have in calcite 808.

In order to switch channels, i.e. to send the signal from input channel 802A to output channel 820B, and the signal from input channel 802B to output channel 802A, the light from input channel 802B arrives at calcite 808 with vertical polarization, and the light from input channel 802A arrives at calcite 808 with horizontal polarization. Then all four beams go to location 808B, the beams from channel 802A because they are not deflected, and the beams from channel 802B because they are deflected. All four beams pass through half-wave plate 809 and have their polarization direction changed by 90 degrees. Then the light that came from input channel 802A has vertical polarization and is deflected upward through calcite 810, reaching output channel 820B, while the light that came from input channel 802B has horizontal polarization, and is not deflected in calcite 810, so goes straight through calcite 810 and reaches output channel 820A.

It should be noted that the eight lines shown in calcite 808 and calcite 810 in Fig. 6 do not represent eight different beams that are present at the same time. Rather, at any given time, there are only four beams present, but the eight beams shown in Fig. 6 represent both possible

locations of each of the four beams, depending on whether the channels are switched or not switched.

Once they emerge from calcite 810, all four beams pass through a half-wave plate 812, oriented with its principle axis either 22.5 degrees or 67.5 degrees from the vertical. This half-wave plate rotates the polarization of the light by 45 degrees, so the polarization of each beam is oriented either 45 degrees to the left of vertical or 45 degrees to the right of vertical, whatever it was before passing through half-wave plate 807 if the channels were not switched, or 90 degrees different from that if the channels were switched. In either case, the polarization is the same as it is for light in the corresponding location (top or bottom) before passing through half-wave plate 807. The light then passes through a controllable polarization rotator 814, which is either active or not depending on whether controllable polarization rotator 806 is active, and emerges with the same polarization as the corresponding location (top or bottom) of light before it has entered controllable polarization rotator 806. Finally, the four beams each pass through a different one of four half-wave plates 816, oriented the same way as corresponding half-wave plates 804, and enter calcites 818A and 818B. Because the two beams that enter each of calcite 818A and 818B have the same polarization as the corresponding beams leaving calcites 800A and 800B, they recombine to form a single beam in each calcite, which emerges from that calcite and enters the corresponding output channel 820A or 820B.

Fig. 7 shows the topology of a router-selector network with four input channels, each of which goes to a different one of four output channels. There are four router sections, each one for a different input channel, but for simplicity, only one such router section 700 is shown in Fig. 7. Each router section consists of three polarizing beam splitters 702, 704, and 706, which can be periscopes or calcites. In Fig. 7, the polarizing beam splitters are shown as periscopes. There is a controllable polarization rotator in front of each periscope. Light from the input channel, assumed to already be polarized (for example using the techniques described above), enters router section 700 at point 708, and passes through controllable polarization rotator 710 before entering periscope 702. Depending on whether controllable polarization rotator 710 is active or inactive, the light entering periscope 702 is directed either to periscope 704 or periscope 706. Controllable polarization rotators 712 and 714 in front of periscopes 704 and 706 direct the light to one of four outputs 716, 718, 720 and 722, depending on whether controllable polarization rotators 712 and 714 are active or inactive.

Controllable polarization rotators 712 and 714 need not be controlled independently. Optionally, both of these controllable polarization rotators are controlled by a single input voltage. If there were eight output channels or 16 output channels, there would be one or two

additional stages of periscopes and controllable polarization rotators in the router. In each stage, all of the controllable polarization rotators are optionally controlled by a single input voltage. The list of input voltages (zero or full voltage) to the controllable polarization rotators in each stage gives the binary code for the desired output. Optionally, if it is expected that the network will frequently switch between adjacent output channels, and it is desired to minimize the amount of changing of input voltages to the controllable polarization rotators, then the list of input voltages gives the Grey code for the desired output instead of the binary code. This is accomplished by wiring some of the controllable polarization rotators so that full input voltage makes the controllable polarization rotator inactive and zero input voltage makes it active.

For each output channel there is a selector section, in which all the inputs going to that output are merged together. In Fig. 7, selector section 724 corresponds to output 716 of router section 700, selector section 726 corresponds to output 718, selector section 728 corresponds to output 720, and selector section 730 corresponds to output 722. Each selector section consists of a branching tree of periscopes, exactly like each of the router sections but in reverse order. The periscopes in the selector sections also optionally have controllable polarization rotators associated with them, in order to block unwanted paths and decrease cross-talk.

Although the selector sections are shown schematically in the same plane as the router section in Fig. 7, in fact it is convenient to stack the router sections, one for each input, above each other in a direction perpendicular to the plane of the drawing. The selector sections are then each laid out in a plane perpendicular to the plane of each router section.

Fig. 8 shows the geometry of periscopes and controllable polarization rotators for either a router section or a selector section. The periscopes are each made up of two cells, not necessarily adjacent to each other, with an optically coated plate mounted diagonally in each cell, and in each periscope one of the cells has a controllable polarization rotator mounted outside it.

The router and selector sections as described up to now are assumed to have polarized input and output. If the real input and output channels use unpolarized light, or light of arbitrary polarization, then it may be desirable to first split the input light into two orthogonally polarized beams, using the entrance stage shown in Fig. 9. An input beam 900 goes into a periscope 902, and is split into two polarized beams 904 and 906. Optionally, a half-wave plate 908 rotates the polarization of one of the beams by 90 degrees, so that the two beams have the same polarization. Each of these beams is then fed into its own router-selector network. Alternatively, the two beams keep their different polarizations when each one enters its own router-selector network, and the layouts of the two networks take this into account. At the end,

the two output beams for each output channel are merged together again, using an exit stage resembling the entrance stage in Fig. 9.

Fig. 10 shows a router-selector network 1000 with four input channels 1002 arranged side by side horizontally, and four output channels 1004 arranged vertically one above the other. Fig. 10 shows the geometry of a router-selector network 1000 in a particular three-dimensional configuration, while Fig. 7 is more schematic, and is primarily intended to show the topology of a router-selector network. The light from input channels 1002 is assumed to be linearly polarized, all in the same direction. If the actual input channels carry light that is not linearly polarized, then the light for each of those input channels may be passed first through an entrance stage such as that shown in Fig. 9, which splits the light into two orthogonally polarized parallel beams and converts them to the same polarization. The light going to each output channel 1004 may be passed through an exit stage similar to the entrance stage, which recombines the two parallel beams into a single beam with the same polarization state (or lack of polarization) as the corresponding input channel had. For the rest of the description of Fig. 10, each input channel will be described as a single polarized beam, but it should be understood that it may comprise two parallel polarized beams, for example if the actual input channels are not all linearly polarized and an entrance stage is provided.

Light entering router-selector network 1000 from input channels 1002 first passes through controllable polarization rotators 1006, one for each input channel. This is the first stage of the router half of the router-selector. In Fig. 4, which shows a router-selector network with two input channels and two output channels, controllable polarization rotators 608A and 608B play the same role as controllable polarization rotators 1006 in Fig. 10. In the case of a router-selector which acts only as a switch, not as multicaster, if the light is initially polarized in the horizontal direction, then ideally it emerges from controllable polarization rotator 1006 with either horizontal polarization (if the controllable polarization rotator does not rotate the polarization) or vertical polarization (if the controllable polarization rotator rotates the polarization by 90 degrees). If the network is being used as a multicaster, combiner, or variable attenuator, then the light may emerge from the controllable polarization rotator with a polarization state that is a linear combination of horizontal and vertical polarization, which in the general case will be elliptically polarized, and in some cases may be linearly polarized at an oblique angle, or circularly polarized. The light then enters the bottom half 1008 of a periscope, and each beam either goes straight through the periscope, or is deflected upward and then deflected again at the top half 1010 of the periscope, emerging in the same direction as it entered, but displaced upward. In Fig. 4, periscopes 610A and 610B play the same role. Light

emerging from lower half 1008 of the periscope then passes through controllable polarization rotators 1012, one for each channel, while light emerging from upper half 1010 of the periscope passes through polarization rotators 1014, one for each channel. This is the second stage of the router section of the router-selector. There is no second stage in the router-selector network shown in Fig. 4, since it only has two input and two output channels, and only needs one stage for the router and one stage for the selector.

If the router-selector network is being used only as a switch, and not as a multicaster or variable attenuator, then optionally controllable polarization rotators 1012 and 1014 can be replaced by a single controllable polarization rotator for each input channel, extending over both the upper and lower light paths for that input channel. This may be done since, in a switch, the light from a given input channel will ideally (ignoring unintended cross-talk) be all in the upper path or all in the lower path, and to the extent that a path has no light, it does not matter what the controllable polarization rotator does on that path. Even if controllable polarization rotators 1012 and 1014 are physically separate, optionally they are controlled together, if the network is being used as a switch. If the network is being used a multicaster, and it is desired to be able to distribute the light from each input channel with any relative power into each output channel, then separate controls are optionally used for controllable polarization rotators 1012 and 1014. If controllable polarization rotators 1012 and 1014 are controlled together, then the network may still be used as a multicaster, but possibly with constraints on how the light may be distributed in the different output channels. For example, the network may be used to distribute light from an input channel equally into all output channels.

Light from controllable polarization rotator 1012 then enters the bottom half 1016 of another periscope, where, depending on its polarization, it either passes straight through, or is deflected to the upper half 1018 of this periscope, where it emerges traveling in the same direction but displaced upward. Light from controllable polarization rotator 1014 enters the bottom half 1020 of another periscope, where it either passes straight through, or is deflected to the upper half 1022 of this periscope, where it emerges traveling in the same direction but displaced upward. For each input channel, there are now four possible paths that the light is following, corresponding to each of the four output channels. For all four input channels, there are a total of 16 possible light paths at this stage. These 16 light paths are arranged in a 4 by 4 array in the embodiment of the invention shown in Fig. 10, but they could be arranged differently.

Eight of the 16 light paths then pass through half-wave plates 1024, which rotate the polarization by 90 degrees. The eight half-wave plates are arranged in a checkerboard pattern in

Fig. 10. If the input and output channels are arranged differently, then the half-wave plates could be arranged in a different pattern. The purpose of half-wave plates 1024 in some embodiments of the invention is to give the light the polarization needed in order to combine all the light paths going into each output channel, in the selector section of the router-selector. Thus, for example, the beam going through the half-wave plate 1024 in the upper left corner is horizontally polarized when it enters the half-wave plate, after reflecting from reflectors 1020 and 1022, and its polarization is rotated to vertical by the half-wave plate so that it is displaced to the right by periscope 1026. But the beam just to the right of this beam, which is also horizontally polarized when it leaves reflector 1022, does not pass through a half-wave plate, and remains horizontally polarized when it enters periscope 1026, allowing it to pass through periscope 1026 without being displaced. Thus these two beams end up following the same path. A similar analysis can be used to show which of the sixteen beams should go through half-wave plates 1024 and which of the beams should not. As noted above in the description of Fig. 1, the foregoing analysis assumes that the polarizing beam splitters reflect all light which is polarized parallel to the coated surface, and transmit all light which is polarized in the other direction. If some or all of the polarizing beam splitters have the opposite behavior, then the analysis will be different, and half-wave plates 1024 may be located at different places, not necessarily making a checkerboard pattern.

These half-wave plates are not shown in Fig. 7, because Fig. 7 is only intended to be schematic, showing the topology of the router and selector. The location of the half-wave plates depends on the geometry of the router-selector, not just on the topology. For example, the location of the half-wave plates depends on whether the input channels are arranged orthogonally to the output channels, as in Fig. 10, or in the same plane as the output channels, as shown schematically in Fig. 7. The location of the half-wave plates also depends on whether the polarizing beam splitters in the selector are of the same type as those in the router (for example, both of reflecting all light which is polarized parallel to the coated surface, and transmitting all light which is polarized in the other direction) or the opposite type.

After passing through the checkerboard pattern of half-wave plates 1024, the light enters the selector section of the router-selector, where all four of the light paths going into the same output channel (i.e. all of the paths on the same level vertically) are optionally combined into a single path. If the network is being used as a switch, then only one of the paths on each level actually has light traveling on it (neglecting cross-talk), but all four paths at each level may have light traveling on them in the case of a variable attenuator, or a network which combines light from more than one input channel into a single output channel. At the first stage

of the selector, for each output channel, the two paths furthest left are combined in periscope 1026, and the two paths furthest right are combined in periscope 1028. Any light emerging from periscope 1026 passes through controllable polarization rotator 1030, and any light emerging from periscope 1028 passes through controllable polarization rotator 1032. Controllable polarization rotators 1030 and 1032 optionally adjust the polarization of light on the two paths so that they will combine into a single path, for each output channel, in the second stage of the selector, in periscope 1034.

If the network is being used as a switch rather than as a multicaster, then optionally controllable polarization rotators 1030 and 1032 may be replaced by a single controllable polarization rotator, for each output channel, similarly to the way that controllable polarization rotators 1012 and 1014 may be replaced by a single controllable polarization rotator for each input channel in the router section.

In the second stage of the selector, periscope 1034 optionally combines the left light path and right light path into a single path, for each output channel. The light emerging from periscope 1034 then optionally passes through a controllable polarization rotator 1036, for each output channel, which restores the polarization the light entering each output channel to the polarization that it had when it entered the router section of the router-selector from one of input channels 1002. The light then enters output channels 1004.

Controllable polarization rotators 1030, 1032, and 1036 also optionally serve to reduce cross-talk by blocking unwanted paths, when the network is used as a switch. These controllable polarization rotators serve this function when they are set to rotate the polarization of the light in each path in such a way that it will end up on the path leading to the output channel. The proper settings of controllable polarization rotators 1030, 1032 and 1036, in order to accomplish this, depend on which input channel is connected to which output channel, i.e. they depend on the settings of controllable polarization rotators 1006, 1012 and 1014 in the router section. Alternatively, any or all of controllable polarization rotators 1030, 1032 and 1036 may be set "incorrectly" for any or all output channels, in order to provide variable attenuation for any or all of the output channels. Alternatively or additionally, it may be possible to provide variable attenuation by setting any or all of controllable polarization rotators 1006, 1012 and 1014 "incorrectly" for any or all input channels.

The router-selector networks shown in Figs. 7 and 10 have a topology in which a router section originating at each input channel has a tree-like structure branching out into as many light paths as there are output channels, and each selector section has a similar tree-like structure in which light paths from all theinput channels merge together to terminate in each

output channel. Although many different tree-like structures are possible, the networks shown in Figs. 7 and 10 in particular use a binary tree structure for both the router sections from each input channel and the selector section going into each output channel. In a binary tree, there are N stages, and at each stage, each light path splits into two light paths at a junction. Thus, in the case of a router section in the form of a binary tree with N stages, each input channel is connected to $2^N$ output channels, and similarly, in a selector section in the form of a binary tree with M stages, each output channel is connected to $2^M$ input channels. In Figs. 7 and 10, both N and M are equal to 2. This topology is a convenient one to use if the desired number of input channels and the desired number of output channels are both equal to a same power of two, but it is not the only topology possible. For example, optionally the number of input channels differs from the number of output channels, so, in the case where both the router sections and selector sections are binary trees, the number of router stages differs from the number of selector stages. Each router section and each selector section need not be a binary tree. For example, if the number of output channels needed is not equal to a power of two, then each router section optionally is a different tree-like structure, which may be thought of as a modified binary tree in which some branches are missing, where a branch is one light path and all the light paths that connect to it going outward from the base of the tree If every input channel is not required to connect to every output channel, then the router sections associated with some input channels optionally differ from the router section associated with other input channels, for example some of them could have fewer stages, or could be missing branches. If it is desired that a first input channel always connects to the same output channel (or the same plurality of output channels in the case of multicasting) as a second input channel, then the light paths from the first and second input channels optionally merge together before going through a router section common to both of them. Alternatively, only some of the branches of the router section originating at the first input channel merge with branches of the router section originating at the second input channel, and only part of their router sections are common to both of them. Similarly, two or more output channels could have all or part of their selector sections in common. Many other variations on network topology are possible, which will be apparent to one skilled in the art.

In describing Fig. 10, it was pointed out that optionally all of the controllable polarization rotators at each stage of each router section, or at each stage of each selector section, are controlled together, or replaced by a single controllable polarization rotator. Such common control does not put any limitations on the operation of such a switching network if the signal from each input channel is being directed to only one output channel, and if each

output channel is receiving a signal from only one input channel, ignoring cross-talk. It is also possible to control other sets of controllable polarization rotators in common, for example controllable polarization rotators from different stages or from different router sections or selector sections. In many cases, such common control will put constraints on the switching or multicasting that is possible.

Figs. 11A-11D show four different designs for bearings that can be used to align and fix optical components in an optical switch or other optical network, either with respect to other components or with respect to a fixed direction in space. These bearings differ in allowing different degrees of freedom of the optical component, rotational and translational, and different ways of limiting the range of motion. As described above for Fig. 2, these bearings optionally contain an adhesive, for example an epoxy, cured by ultraviolet light or by heat. Alternatively or additionally, another means is used to cure the adhesive. Once the component is aligned with respect to one or more other optical components, or with respect to an absolute direction in space, the adhesive is cured and the component is fixed in place. Any of the bearings shown in Figs. 11A-11D optionally serve as bearing 311 in Fig. 2.

In some embodiments of the invention, the adhesive is applied to the bearing before the bearing is aligned. Particularly in these embodiments of the invention, the adhesive optionally has low enough viscosity before it is cured so that it does not noticeably hinder the alignment of the bearing. Alternatively or additionally, the adhesive has a high enough viscosity before curing so that it prevents the bearing from slipping, between the time it is aligned and the time it is fixed in place by curing the adhesive. However, other means could also be used to keep the bearing from slipping during this time, for example set screws, and it may be desirable not to rely on the viscosity of the adhesive for this purpose, but to keep the viscosity as low as possible to allow easy alignment of the bearing.

Optionally, whether the adhesive is applied before or after the bearing is aligned, the bearing has one or more channels for injecting the adhesive. Optionally, these channels extend through a substrate on which the bearing is mounted, so that the openings of the channels are easily accessible after the optical switch is assembled.

In Fig. 11A, an optical component 1998 is mounted on a hollow cylinder 2002. Cylinder 2002 fits around a cylinder 2004, which is fixed to a substrate which holds other optical components. Adhesive is provided between the cylinders. Optionally, the adhesive is space-filling. Alternatively, the adhesive is not significantly space-filling. (These options also apply to the adhesive in the embodiments of the invention shown in Figs. 11B-11D and Fig. 12.) Optical component 1998 can be moved axially by sliding cylinder 2002 along cylinder

2004, as indicated by arrow 2008. By rotating cylinder 2002 around cylinder 2004, as indicated by arrow 2010, optical component 1998 undergoes a combination of rotation around the axis of the cylinders, and translation in a horizontal direction perpendicular to the axis of the cylinders. If optical component 1998 is not attached to cylinder 2002, but is free to roll around cylinder 2002, then it has separate translation and rotational degrees of freedom, in addition to its translation degree of freedom along the axis. Optionally, optical component 1998 is constrained from rotating when cylinder 2002 rotates but is free to translate horizontally perpendicular to the axis, for example by putting a track above it which fits closely around two of the edges of the top. Optionally, stops 2006 at the ends of cylinder 2004 limit the motion of cylinder 2002 and optical component 1998 axially.

Fig. 11B shows an optical component 1998 mounted on a cylinder 2020, which is surrounded by a hollow cylinder 2022, and having adhesive provided between the cylinders. Hollow cylinder 2022 is attached to a substrate which holds other optical components. Cylinder 2020, together with optical component 1998, is free to rotate with respect to cylinder 2022, as indicated by a curved arrow 2024, and to move up and down, as indicated by an arrow 2026. Optionally, stops, for example attached to cylinder 2020, limit the up and down motion of cylinder 2020 with respect to cylinder 2022. Optical component 1998 optionally limits its downward motion when it touches cylinder 2022, if nothing else limits the motion sooner.

Fig. 11C shows an optical component 1998 mounted on a platform 2034, which rests on a spherical bearing 2030, which is held within a track 2032, which is attached to a substrate which holds other optical components. Adhesive is optionally provided between platform 2034 and the top of track 2032. Additionally or alternatively, adhesive is provided between spherical bearing 2030 and the inside of track 2032. Track 2032 has the form of a horizontally oriented cylinder with its top sliced off. Optionally, less than half of the cylinder is sliced off, and the diameter of spherical bearing 2030 is almost equal to the inner diameter of track 2032, and bearing 2030 is not removed from track 2032 except by going out one of the ends of track 2032. Optical component 1998 is free to rotate about the vertical axis, as indicated by a curved arrow 2038, and it is free to move axially, as indicated by an arrow 2039, by having platform 2034 roll along the top of bearing 2030 while bearing 2030 rolls in track 2032.

Optionally, rods 2036, mounted across the opening at the top of track 2032, limit the axial motion of platform 2034, for example either because platform 2034 touches rods 2036, or because bearing 2030 touches rods 2036. Optionally, rods 2036 also constrain platform 2034 from moving vertically and/or horizontally perpendicular to the axis of track 2032. This is optionally done, for example, by having platform 2034, or extensions of platform 2034, pass

under rods 2036, and/or pass above rods 2036. Platform 2034 or its extensions optionally constrain bearing 2030, and optical component 1998, from rotating around one or more of its three principle axes, and/or they constrain optical component 1998 from moving horizontally, in a direction perpendicular to the axis of track 2032, because the platform or the extensions touch one or both of rods 2036. Alternatively, rods 2036 do not completely prevent platform 2034 from moving in these directions, but rods 2036 only limit the motion of platform 2034 in one or more of these directions, or they do not limit its motion at all in one or more of these directions. Even if rods 2036 do not constrain the motion of platform 2034 in a given direction, other constraints optionally limit the rotation of bearing 2030 and optical component 1998 around one or more of its axes, or limit the translation of optical component 1998 in a horizontal direction perpendicular to the axis of track 2032. For example, the rotation of bearing 2030 is optionally limited by platform 2034 or its extensions touching track 2032.

Fig. 11D shows a spherical bearing 2044 surrounded by a hollow spherical shell 2040, in which adhesive is provided between spherical bearing 2044 and spherical shell 2040. There is a circular opening 2046 at the top of shell 2040, and V-shaped extensions 2042 of opening 2046, extending in four different directions. Alternatively, opening 2046 is a different shape. Optionally, spherical shell 2040 is made of two or more parts, each covering no more than a hemisphere, which are assembled around spherical bearing 2044. An optical component 1998 is mounted on a stem 2048 attached to bearing 2044, and shell 2040 is attached to a substrate, not shown in Fig. 11D, which holds other optical components. The optical component can be oriented in any direction by rotating bearing 2044 inside shell 2040. The possible orientations of the optical component are constrained by the requirement that the point on bearing 2044 where the stem is attached is exposed to opening 2046 or its extensions 2042. As the stem moves into one of V-shaped openings 2042 and gets closer to vertex 2050, then bearing 2044 will have decreasing freedom to rotate in a direction that would cause the stem to hit the sides of the V-shaped opening, although it will still be free to rotate around the axis in the direction of the stem, and to rotate in a direction such that the stem will towards or away from vertex 2050. The degree and direction of the constraints on rotation of bearing 2044 depend on where the stem is located with respect to the openings in shell 2040.

Optionally, a mounting 2052 joining the optical component to the stem has one or more degrees of rotational and translation freedom, and optionally the degrees of freedom of the mounting can be locked. For example, optionally the mounting is similar to a camera mounting on a tripod. This mounting allows the optical component to be oriented in any direction and positioned at any location, possibly within some limits, for any orientation of bearing 2044

with respect to shell 2040. The mounting is optionally used to adjust the position and orientation of the optical component coarsely, while fine adjustments are made by rotating bearing 2044 in shell 2040. The position of the stem relative to the openings of shell 2040 is optionally adjusted so that, when the mounting is locked, the orientation of the optical component is constrained to the desired degree and in the desired direction for making fine adjustments.

Fig. 12 shows an optical element 1200 in which the optical components themselves comprise a bearing which is used to change the orientation and/or position of the optical axis. Optical element 1200 comprises a spherical convex lens 1202 mounted on a substrate 1203 which also has other optical elements mounted on it, and a spherical concave lens 1204 of nearly the same curvature, which fits closely against lens 1202. An optical quality adhesive is located between the two lenses. The two lenses are free to rotate and slide relative to each other, like a ball and socket joint, thereby deflecting light that passes through the lenses, allowing the light path to be aligned with the other optical elements. Optionally there is a housing, not shown in Fig. 12, which keeps lens 1202 and lens 1204 from separating.

For example, a ray of light 1206, traveling along the optical axis of lens 1202, enters a flat surface 1208 of lens 1202, normal to the optical axis, so light ray 1206 is not deflected when entering the lens. Lens 1204 has the same index of refraction as lens 1202, and the gap between the two lenses is very small, so light ray 1206 continues on the same line when it enters lens 1204. When light ray 1206 leaves the flat surface 1210 of lens 1204, it reaches surface 1210 at an oblique angle, so it is deflected by an angle given by Snell's law. The orientation of surface 1210 relative to surface 1208 is adjustable by sliding the lenses against each other, so the direction along which the light ray is travels after leaving lens 1204 is also adjustable.

Optionally, one or both of surfaces 1208 and 1210 are curved rather than flat, and/or the two lenses have different indexes of refraction, so the lenses focus or spread the light in addition to deflecting it. Optionally surfaces 1208 and 1210 have any other shape, for manipulating the light. Optionally, the surfaces where the lens are in contact are not spherical, but astigmatic, or even cylindrical, and the lenses can only change their relative orientation in one degree of freedom, instead of two or three. If the lens have the same index of refraction and there is no significant gap between them, then the astigmatism of these surfaces will not affect the light ray. If the astigmatism of the surfaces does affect the light ray, the effect can be compensated by another lens (not shown). Optionally, the surfaces are not astigmatic, but are aspherical, for example parabolic. If the departure of the surfaces from spherical shape is not

very great, then the lens may be able to slip against each other by a limited amount, due to the imperfect fit of the two surfaces, and this can be used to limit the range of orientation of the light ray. If the surfaces in contact with each other are not astigmatic, but are not spherical, then the lenses will be free to rotate relative to each other, but not to slide in other directions. If surface 1208, for example, is flat and normal to the axis of rotation of the surfaces in contact, and surface 1210 is flat but not parallel to surface 1208, then rotating lens 1204 will change the direction in which the light ray leaves lens 1204, but the angle of deflection of the light ray will remain the same. If, in this example, surface 1210 is astigmatic, then rotating lens 1204 will change the orientation of the astigmatism of the light ray emerging from lens 1204. Many other ways of using the motion of one or both lenses to control the direction or focal properties of the light ray will occur to persons skilled in the art.

Optionally, instead of the light beam going through lenses comprised by a ball and socket like bearing, the lenses are used only structurally in the ball and socket like bearing, and the light beam goes through other lenses, or other optical components, mounted on the bearing. Even if light does not pass through the bearing, it may still be advantageous to use lenses to construct ball and socket bearings, rather than other materials, because of their availability in a large variety of diameters and curvatures, their ease of use, low weight, and low price (if they are not of high optical quality).

As used herein, the term "ball and socket joint" refers to any joint in which a convex curved surface fits and slips against a concave curved surface, even if one or both of said surfaces comprise only a small part of the surface of a complete sphere, and even if the surfaces are not spherical, but some other shape. For example, one or both surfaces could comprise a lens with diameter small compared to its radius of curvature, and/or with an aspherical surface, and/or with astigmatism.

Whether or not a ball and socket joint comprises lenses, and whether or not light goes through the lenses, excess adhesive between the ball and the socket can cause the optical paths to become misaligned. A solution to this potential problem is illustrated in Figs. 13A and 13B. Fig. 13A shows a side view of a ball and socket joint 1300 with a ball 1302 at the top resting on a socket 1304 at the bottom, and an optical component 1306 attached to the ball, and a substrate 1308 attached to the socket. Optionally, ball 1302 is replaced by a partial ball comprising a convex lens, and socket 1304 comprises a concave lens. Optionally, in this case, there is a structure, not shown, which keeps ball 1302 from separating from socket 1304. Curable adhesive is applied to the bottom of ball 1302, and grooves 1310, cut into socket 1304, allow excess adhesive to drain away. The grooves prevent excess adhesive from causing non-

uniformities of the adhesive layer or raising ball 1302 away from the surface of socket 1304, possibly to an unpredictable degree that depends on the condition of the adhesive, and misaligning the optical components. Fig. 13B, a top view of socket 1304 and substrate 1308, shows, as an example, two grooves 1310 cut perpendicular to each other. Alternatively, there is only one groove, or there are two or more grooves parallel to each other, or the grooves are located in other positions. Optionally, similar grooves are used in other bearings that are used to align optical components, for example those shown in Figs. 11A-11D.

As used herein with regard to optical elements on a substrate, the term "joint" refers to any support structure comprising two coupled parts which move relative to each other, whether the relative motion involves rotation, translation, or both.

The invention has been described in the context of the best mode for carrying it out. It should be understood that not all features shown in the drawings or described in the associated text may be present in an actual device, in accordance with some embodiments of the invention. Furthermore, variations on the method and apparatus shown are included within the scope of the invention, which is limited only by the claims. Also, features of one embodiment may be provided in conjunction with features of a different embodiment of the invention. As used herein, the terms "have", "include" and "comprise" or their conjugates mean "including but not limited to." The term "calcite" is used herein to mean any birefringent crystal which is used as a polarizing beam splitter, including synthetic materials such as yttrium vanadate.

# CLAIMS

1. An optical router-selector comprising:

at least four channels, including at least one input channel and at least one output channel;

a plurality of optical junction elements controllable to direct light from any input channel to any of the at least one output channels, wherein each element couples three optical paths, and comprises at least one controllable polarization rotator, the state of which determines whether and how much of light entering one of the paths exits through at least one of the other paths; and

a controller which controls the state of each controllable polarization rotator,

wherein the controller is configured to control all of the members of at least one set of two or more of the controllable polarization rotators to be in a same state at a given time.

2. An optical router-selector according to claim 1, wherein, for at least one of the at least one sets, all of the controllable polarization rotators belonging to said set are comprised in junction elements that are splitters, configured so that light enters only one path and exits through either or both of the other paths.

3. An optical router-selector according to claim 2, wherein each of said splitters receive light from a same input channel, and not from any other input channel.

4. An optical router-selector according to claim 1, wherein no two members of said set are arranged in series along a same light path.

5. An optical router-selector according to claim 3, wherein said at least one sets whose members are comprised only by splitters, comprise a plurality of sets with no members in common, and wherein no two members of any set in said plurality of sets are arranged in series along a same light path, and wherein for all of the sets in said plurality of sets, the splitters receive light from a same input channel, and not from any other input channel.

6. An optical router-selector according to claim 5, wherein a router section originating at said input channel comprises a tree structure, within which tree structure all of the junction elements are splitters.

7. An optical router-selector according to claim 6, wherein all the splitters of said tree structure are arranged in N ordered router stages, such that no light path goes through more than one splitter in each router stage, and for any two positive integers i and j, where $i < j \leq N$, any light path that goes through splitters in both the ith router stage and the jth router stage goes through the splitter in the ith router stage before going through the splitter in jth router stage, and wherein for each set in said plurality of sets, all the splitters are in a same router stage.

8. An optical router-selector according to claim 7, wherein within said tree structure, all the controllable polarization rotators comprised by each router stage which comprises more than one controllable polarization rotator, belong to a same set in said plurality of sets.

9. An optical router-selector according to claim 8, wherein every light path in said tree structure passes through a splitter belonging to each router stage, whereby the tree structure is a binary tree structure in which there are $2^{m-1}$ splitters at the mth router stage.

10. An optical router-selector according to claim 9, wherein for every input channel, a router section originating at that input channel comprises a binary tree structure, in which all the controllable polarization rotators comprised by the splitters at each router stage except the first router stage belong to a same one of the sets, and no two controllable polarization rotators comprised by the splitters at different router stages belong to a same one of the sets.

11. An optical router-selector according to claim 1, wherein, for at least one of the at least one sets, all of the controllable polarization rotators belonging to said set are comprised by junction elements that are joiners, configured so that light exits only one path and enters through either or both of the other paths.

12. An optical router-selector according to claim 11, wherein each of said joiners direct light toward a same output channel, and not toward any other output channel.

13. An optical router-selector according to claim 12, wherein said at least one sets whose members are comprised only by joiners comprise a plurality of sets with no members in common, and wherein no two members of any set in said plurality of sets are arranged in series along a same light path, and wherein for all of the sets in said plurality of sets, the joiners direct light toward a same output channel, and not toward any other output channel.

14. An optical router-selector according to claim 13, wherein a selector section terminating at said output channel comprises a tree structure, within which tree structure all of the junction elements are joiners.

15. An optical router-selector according to claim 14, wherein all the joiners of said tree structure are arranged in M ordered selector stages, such that no light path goes through more than one joiner in each selector stage, and for any two positive integers i and j, where $i < j \leq M$, any light path that goes through joiners in both the ith selector stage and the jth selector stage goes through the joiner in the ith selector stage after going through the joiner in jth selector stage, and wherein for each set in said plurality of sets, all the joiners are in a same selector stage.

16. An optical router-selector according to claim 15, wherein within said tree structure, all the controllable polarization rotators comprised by each selector stage which comprises more than controllable polarization rotator, belong to a same set in said plurality of sets.

17. An optical router-selector according to claim 16, wherein every light path in said tree structure passes through a joiner belonging to each selector stage, whereby the tree structure is a binary tree structure in which there are $2^{m-1}$ joiners at the mth selector stage.

18. An optical router-selector according to claim 17, wherein for every output channel, a selector section terminating at that output channel comprises a binary tree structure, in which all the controllable polarization rotators comprised by the joiners at each selector stage except the first selector stage belong to a same one of the sets, and no two controllable polarization rotators comprised by joiners at different selector stages belong to a same one of the sets.

19. An optical router-selector according to any of the preceding claims, wherein any light path through which light exits from a splitter does not lead to a same output channel as the other light path through which light exits from said splitter.

20. An optical router-selector according to any of claims 1-18, wherein any light path through which light enters a joiner does not come from a same input channel as the other light path through which light enters said joiner.

21. An optical router-selector according to any of claims 1-18, wherein the number of input channels is equal to the number of output channels.

22. An optical router-selector according to any of claims 1-18, wherein at least one of the at least one sets of commonly controlled polarization rotators comprise a single controllable polarization rotator.

23. An optical router-selector according to any of claims 1-18, wherein each of the at least one sets of commonly controlled polarization rotators is comprised by a single controllable polarization rotator.

24. A router-selector optical switching network according to any of claims 1-18, wherein a signal from at least one input channel is distributed to more than one output channel.

25. A router-selector optical switching network according to any of claims 1-18, wherein at least one output channel obtains combined signals from two or more input channels.

26. A router-selector optical switching network according to any of claims 1-18, wherein at least one controllable polarization rotator controls a degree of attenuation of at least one output channel.

27. An optical router-selector according to any of claims 1-18, wherein all the light paths from each input channel pass through a router section that comprises any splitters that said light paths pass through, before said light paths pass through any joiners.

28. An optical router-selector according to any of claims 1-18, wherein all the light paths going to each output channel pass through a selector section that comprises any joiners that said light paths pass through, after said light paths pass through any splitters.

29. An optical router-selector according to any of claims 1-18, wherein the light paths of each router section are co-planar, the light paths of each selector section are co-planar, the planes of all the router light paths are parallel to each other, the planes of all the selector light paths are parallel to each other, and the planes of all the router light paths are perpendicular to the planes of all the selector light paths.

30. An optical router-selector according to any of claims 1-18, wherein at least one of the junction elements comprises a polarizing beam splitter.

31. An optical configuration, comprising:

a substrate;

at least a first optical element, with an optical axis, which element is coupled to said substrate;

a bearing comprising at least one joint formed between the first element and said substrate, such that the first element can be oriented on said bearing in a plurality of orientations; and

a curable adhesive in the joint, which, when said adhesive is cured, fixes an orientation of said joint.

32. An optical configuration according to claim 31, and including a second optical element with an optical axis, which second element is coupled to the substrate, wherein the first element can be oriented on the bearing in an orientation which brings the optical axis of the first element into substantial alignment with the optical axis of the second element.

33. An optical configuration according to claim 32, wherein the first element can be moved on the bearing into a plurality of positions, in at least some of which positions the optical axis of the first element has a common orientation, and the first element can be moved on the bearing into a position and an orientation which brings the optical axis of the first element into substantial alignment with the optical axis of the second element.

34. An optical configuration according to claim 33, wherein the bearing allows the first element to rotate about at least one axis and to slide along at least one axis.

35. An optical configuration according to any of claims 31-34, wherein at least one of the at least one joints comprises a ball and socket joint.

36. An optical configuration according to any of claims 31-34, wherein for at least some orientations of the first element the bearing allows the first element to rotate about at least one axis, and including a rotation limiter which limits the range of rotation of the first element about said axis when the first element is in at least some orientations.

37. An optical configuration according to claim 36, wherein said rotation limiter is configured so that said range of rotation is adjustable.

38. An optical configuration, comprising:

a substrate; and

at least a first optical element, with an optical axis, and including at least one convex surface and at least one concave surface, which element is coupled to said substrate;

wherein at least one of the at least one convex surfaces comprises a ball of a ball and socket joint, and at least one of the at least one concave surfaces comprises a socket of said ball and socket joint, such that the ball can be oriented relative to the socket in a plurality of orientations.

39. An optical configuration, comprising:

a substrate;

at least a first optical element, with an optical axis;

a ball and socket joint coupling said first optical element to said substrate, the ball of which comprises a convex lens and the socket of which comprises a concave lens;

wherein the ball can be oriented relative to the socket in a plurality of orientations.

40. An optical configuration according to claim 38 or claim 39, and including at least a second optical element coupled to the substrate, wherein the ball can be oriented relative to the

socket so that the optical axis of the first element is substantially aligned with the optical axis of the second element.

41. An optical configuration according to claim 38 or claim 39, wherein one or both of the ball and the socket are aspherical, and the asphericity limits the range of orientations of the ball relative to the socket.

42. An optical configuration according to claim 38 or claim 39, and including a housing which keeps the ball from separating from the socket.

43. An optical configuration according to claim 38 or claim 39, and including a curable adhesive in the ball and socket joint, which adhesive fixes an orientation of said ball and socket joint when said adhesive is cured.

44. An optical configuration according to any of claims 31-34, wherein the curable adhesive is cured by ultraviolet light.

45. An optical configuration according to any of claims 31-34, wherein one or more of said first element, said substrate and said bearing is transparent to ultraviolet light.

46. An optical configuration according to any of claims 31-34, wherein the curable adhesive is cured by heat.

47. An optical configuration according to any of claims 31-34, wherein said adhesive is viscous and prevents slipping of said bearing when no external forces are applied to said first optical element.

48. An optical configuration according to any of claims 31-34, and including at least one groove formed in the joint which is positioned such that excess amounts of the adhesive drain away from the joint via the groove.

49. An optical configuration according to claim 48, wherein the at least one groove comprises two grooves.

50. An optical configuration according to claim 49, wherein the two grooves are perpendicular to each other.

51. A polarizing beam-splitter apparatus, comprising:

an input port through which an input beam of light is provided;

a first polarizing beam splitter that receives the input beam and splits the beam into at least a first and second beam, said first beam having substantially a first desired polarization state and said second beam having a second polarization state orthogonal to said first polarization state but possibly admixed with the first polarization state; and

an optical system that receives the second beam and provides a third beam having the second polarization state and a smaller admixture of the second polarization state than the second beam.

52. A polarizing beam-splitter apparatus according to claim 51 wherein the first beam splitter comprises a first planar surface that reflects light having the second polarization state and transmits light having the first polarization state and wherein the input beam is incident on the surface at a first angle.

53. A polarizing beam-splitter apparatus according to claim 52 wherein the first angle is substantially 45$^{o}$.

54. A polarizing beam-splitter apparatus according to any of claims 51-53, wherein the optical system comprises a polarizing beam splitter that receives the second beam and splits the second beam into the third beam and a fourth beam having substantially the first polarization state.

55. A polarizing beam-splitter apparatus according to any of claims 51-53 wherein the optical system comprises a second beam splitter having a second planar surface that reflects light having the second polarization state and transmits light having the first polarization state and wherein the second beam is incident on the second planar surface at a second angle and light reflected by the second surface from the second beam forms the third beam and light transmitted by the second surface forms a fourth beam.

56. A polarizing beam-splitter apparatus according to claim 55 and comprising an absorber that receives the fourth beam.

57. A polarizing beam-splitter apparatus according to claim 55 wherein the second angle is substantially 45°.

58. A polarizing beam-splitter apparatus according to claim 55 wherein the first and second surfaces are substantially parallel as a result of which, the first and third beams are parallel and displaced from each other.

59. A polarizing beam-splitter apparatus according to claim 55 wherein the first and second surfaces are surfaces formed on a same substrate material substantially transparent to light in the input beam.

60. A polarizing beam-splitter apparatus according to any of claims 51-53 and comprising:

at least one controllable polarization rotator positioned to receive one of the first and third beams and operable to change the polarization state of the beam it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received beam responsive to the polarization state of the beam.

61. A polarizing beam-splitter apparatus according to claim 60 wherein the at least one controllable polarization rotator comprises a polarization rotator for each of the first and second beams.

62. A polarizing beam-splitter apparatus according to claim 60 wherein the polarization rotator comprises:

at least one volume of PLZT through which light received by the rotator is transmitted; and

at least one electrode for applying a voltage to the volume of PLZT, which voltage controls the state to which the rotator changes the polarization of light that the rotator receives.

63. Apparatus according to claim 60, comprising a pair of polarization rotators arranged around said polarization controller, to rotate polarization of light entering and exiting said controller.

64. Apparatus according to claim 63, wherein an electric field direction of said controller is perpendicular to a plane common to said beams.

65. An optical switch comprising an input port through which the switch receives light and first and second output ports to which the switch selectively directs light that it receives comprising:

a first polarization state apparatus that receives light from the input port and provides a light beam having a desired polarization state;

a polarizing beam-splitter apparatus according to any of claims 51-53 that receives the light beam from the polarization state apparatus at the beam splitter apparatus input port and generates at least one first beam and/or at least one third beam responsive to the polarization of the light that it receives; and

wherein the first output port receives light from the at least one first beam and the second output port receives light from the at least one third beam.

66. An optical switch according to claim 65 and comprising:

a polarizing beam splitter that receives light from the input port and generates fifth and sixth spatially separated beams therefrom said fifth beam having substantially a third polarization state and said sixth beam having a fourth polarization state substantially orthogonal to the third state;

a second polarization state apparatus that receives the first and second beams of light and changes the polarization state of at least one of the fifth and sixth beams so that the polarization state of both beams is the same; and

wherein the fifth and sixth beams are directed to the input port of the beam splitter apparatus, which apparatus generates a first and/or third beam responsive to the fifth beam and a first and/or third beam responsive to the sixth beam.

67. An optical switch according to claim 66 comprising a first polarizer through which light from the first beams from the polarizing beam-splitter apparatus is transmitted and wherein said first polarizer transmits substantially only light having the first polarization state.

68. An optical switch according to claim 66 comprising a second polarizer through which light from the third beams from the polarizing beam-splitter apparatus is transmitted and

wherein said second polarizer transmits substantially only light having the second polarization state.

69. An optical switch according to claim 66 comprising:

an first optical combiner that combines light in the first beams provided by the beam splitter apparatus responsive to light in the fifth and sixth beams and directs the combined light to the first output port.

70. An optical switch according to claim 69 comprising:

a second optical combiner that combines light in the third beams provided by the beam splitter apparatus responsive to light in the fifth and sixth beams and directs the combined light to the second output port.

71. An optical switch according to claim 69 wherein the first optical combiner comprises:

a third polarization state apparatus that receives the first beam provided from light in the fifth beam and transmits the light in the third polarization state and receives the light in the first beam provided by light from the sixth beam and transmits the light in the fourth polarization state;

an optical joiner that receives light in first beams from the third polarization state apparatus and combines the received light into a single beam that is transmitted to the first output port.

72. An optical switch according to claim 70 wherein the second optical combiner comprises:

a fourth polarization state apparatus that receives the third beam provided from light in the fifth beam and transmits the light in the third polarization state and receives the light in the third beam provided by light from the sixth beam and transmits the light in the fourth polarization state;

an optical joiner that receives light in the third beams from the fourth polarization state apparatus and combines the received light into a single beam that is transmitted to the second output port.

73. An optical switch according to claim 69 and comprising a first controllable attenuator controllable to attenuate light from the first combiner by a desired attenuation before the light reaches the first output port.

74. An optical switch according to claim 70 and comprising a second controllable attenuator controllable to attenuate light from the second combiner by a desired attenuation before the light reaches the second output port.

75. An optical switch according to claim 73 wherein the first attenuator comprises:

at least one controllable polarization rotator positioned to receive the light from the first combiner and operable to change the polarization state of the light it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received beam responsive to the polarization state of the light.

76. An optical switch according to claim 74 wherein the second attenuator comprises:

at least one controllable polarization rotator positioned to receive the light from the second combiner and operable to change the polarization state of the light it receives; and

a polarizer that receives the beam from the rotator and transmits an amount of optical energy in the received responsive to the polarization state of the light.

77. An optical switch according to claim according to claim 75 wherein the polarization rotator comprises:

at least one volume of PLZT through which light received by the rotator is transmitted; and

at least one electrode for applying a voltage to the volume of PLZT, which voltage controls the state to which the rotator changes the polarization of light that the rotator receives.

78. A switch array comprising a plurality of switches according to claim 65, sharing an elongated optical element, said elongation being perpendicular to a plane of each of said switches.

79. A switch according to claim 65, comprising at least one reflector for folding an optical path of said switch.

80. A compound optical switch comprising at least two optical switches according to claim 65 wherein the first output port of each optical switch is a same single first shared output port and the second output port of each optical switch is a same single second shared output port.

81. A compound optical switch comprising a cascade of optical switches wherein an n-th tier of the cascade comprises $2^n$ optical switches according to claim 65 and wherein light from the first and second output ports of an optical switch in the n-th tier is input to the input ports of two optical switches in the (n+1)-st tier.

82. A compound optical switch according to claim 81 wherein each optical switch in the n-th tier receives light from only a single output port of the optical switches in the (n-1)st tier.

83. A compound optical switch according to claim 81 comprising N tiers and comprising an output port that receives light from at least two output ports of the optical switches in the n-th tier.

84. A router-selector optical switching network, comprising:

a number of input channels equal to a power of two;

a number of output channels equal to the same or a different power of two;

a router section for each input channel comprising a binary branching tree of polarizing beam splitters, light paths joining them, and controllable polarization rotators;

a selector section for each output channel comprising a binary branching tree of polarizing beam joiners, light paths joining them, and controllable polarization rotators;

wherein the controllable polarization rotators operate to control the connection of any output channel to at most one input channel and any input channel to at most one output channel.

85. A router-selector optical switching network according to claim 84, wherein the light paths of each router are co-planar, the light paths of each selector are co-planar, the planes of all the router light paths are parallel to each other, the planes of all the selector light paths are parallel to each other, and the planes of all the router light paths are perpendicular to the planes of all the selector light paths.

86. A router-selector optical switching network according to claim 84 or claim 85, wherein at least one of the polarizing beam splitters or one of the polarizing beam joiners is a polarizing beam splitter apparatus according to any of claims 51-53.

87. A method of aligning a first optical element with a second optical element comprising:

mounting the first optical element on a first part of a support comprising first and second parts, wherein the first part is movably coupled to the second part;

mounting the second part of the support in a fixed position relative to the second optical element;

applying a curable adhesive to the support so that the adhesive contacts both the first and second parts;

moving the first part so that the first optical element is aligned with the second optical element; and

curing the adhesive to secure the first part in the aligned position.

88. An optical configuration, comprising:

a substrate;

at least two optical elements that lie in a same path and are coupled to said substrate; and

at least one ball and socket joint formed between at least one of said elements and said substrate, such that said one element can be oriented on said joint in a plurality of orientations relative to the other one of said elements.

89. An optical configuration according to claim 88, and including curable adhesive in the bearing.

90. An optical configuration according to claim 89, wherein the curable adhesive is cured by ultraviolet light.

91. An optical configuration according to any of claims 88-90, wherein said adhesive is viscous and prevent slipping of said joint when no external forces are applied to said optical element.

92. An optical configuration according to any of claims 88-90, wherein said one optical element or said substrate is transparent to ultraviolet light.

93. An optical configuration according to any of claims 88-90, wherein said ball is on said substrate.

94. An optical configuration according to any of claims 88-90, wherein said ball is on said element.

95. An optical configuration according to any of claims 88-90, wherein said ball is integral to one of said substrate and said element.

96. An optical configuration according to any of claims 88-90, wherein said ball is mounted on one of said substrate and said element.

97. An optical configuration according to claim 96, wherein said ball is attached using an adhesive to said one of said substrate and said element.

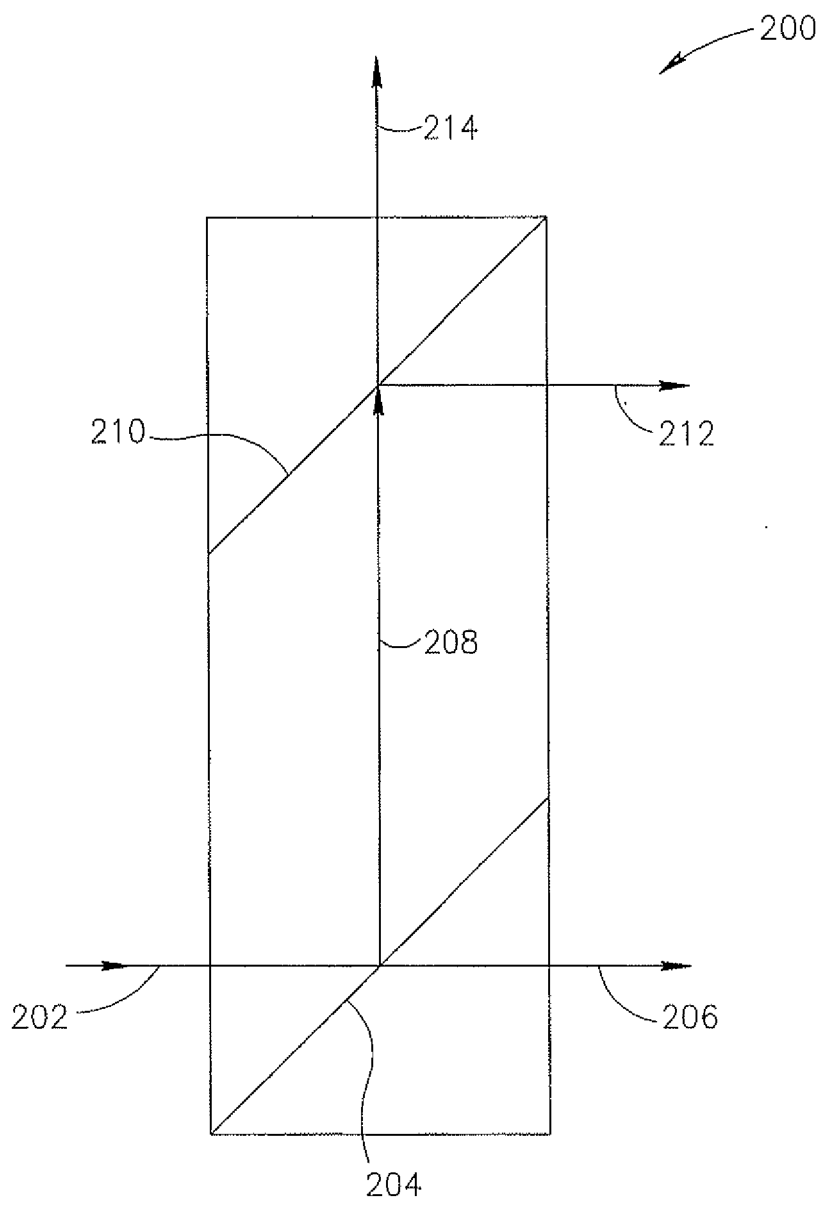
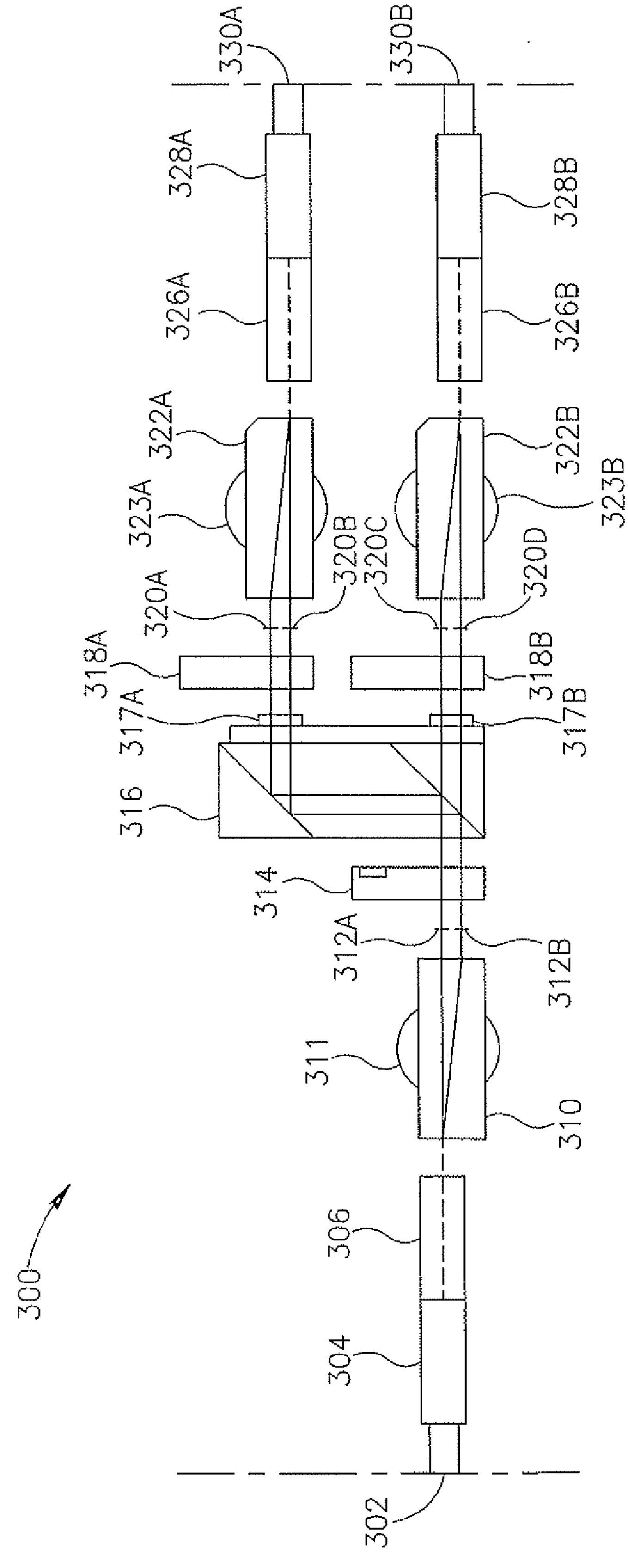



FIG.1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330A
330B

FIG.2

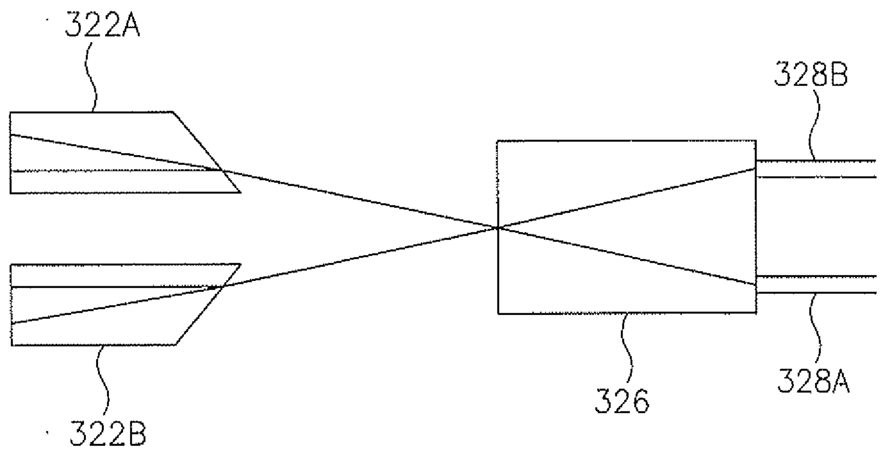
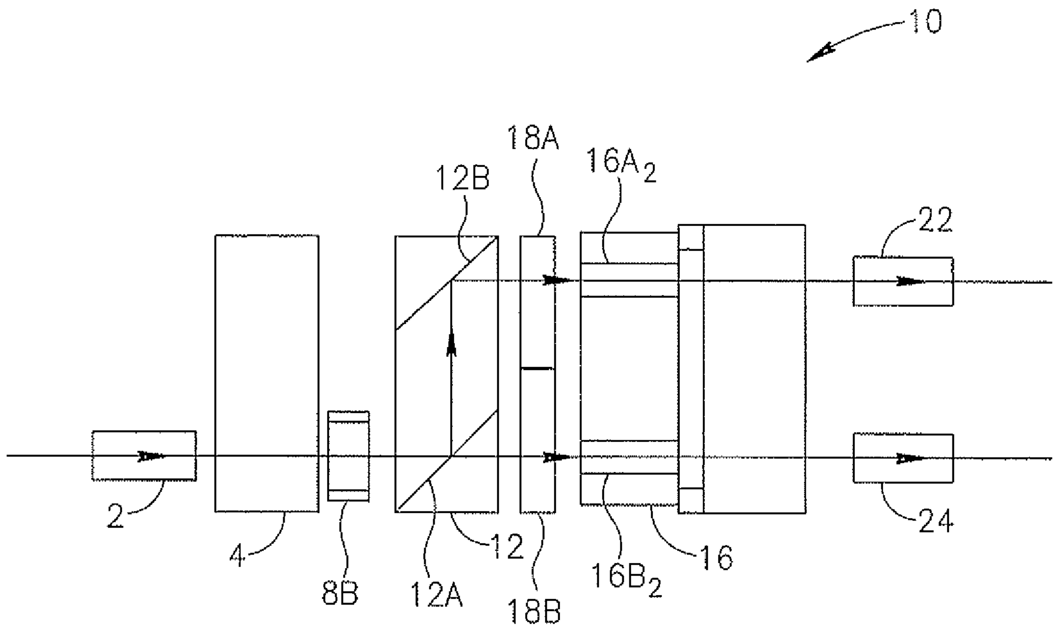



FIG.2A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12A
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18B
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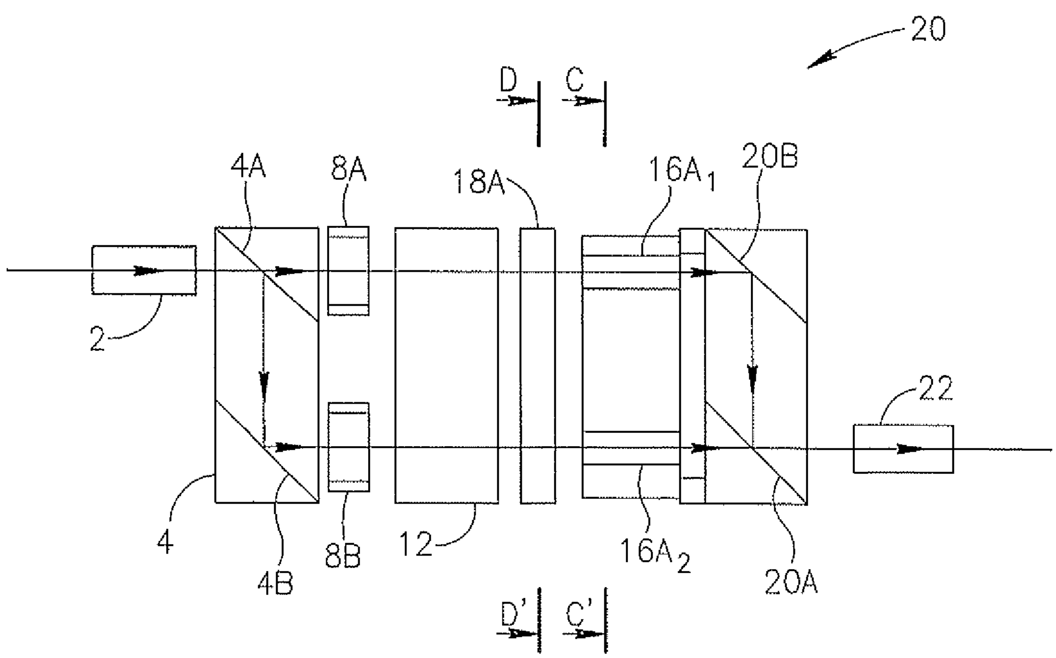
16
24

FIG.3A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16A2
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C'

FIG.3B

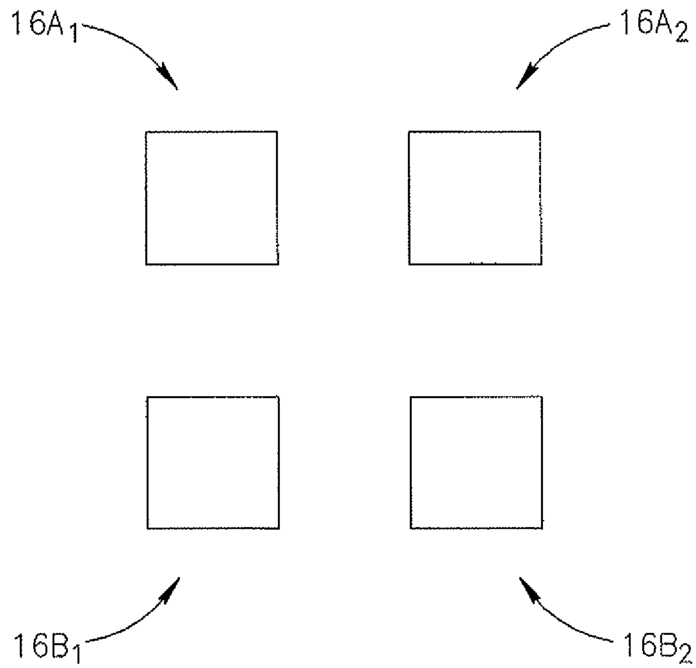



FIG.3C

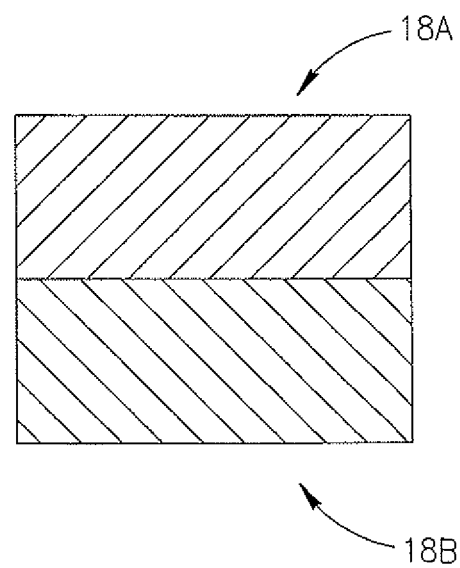



FIG.3D

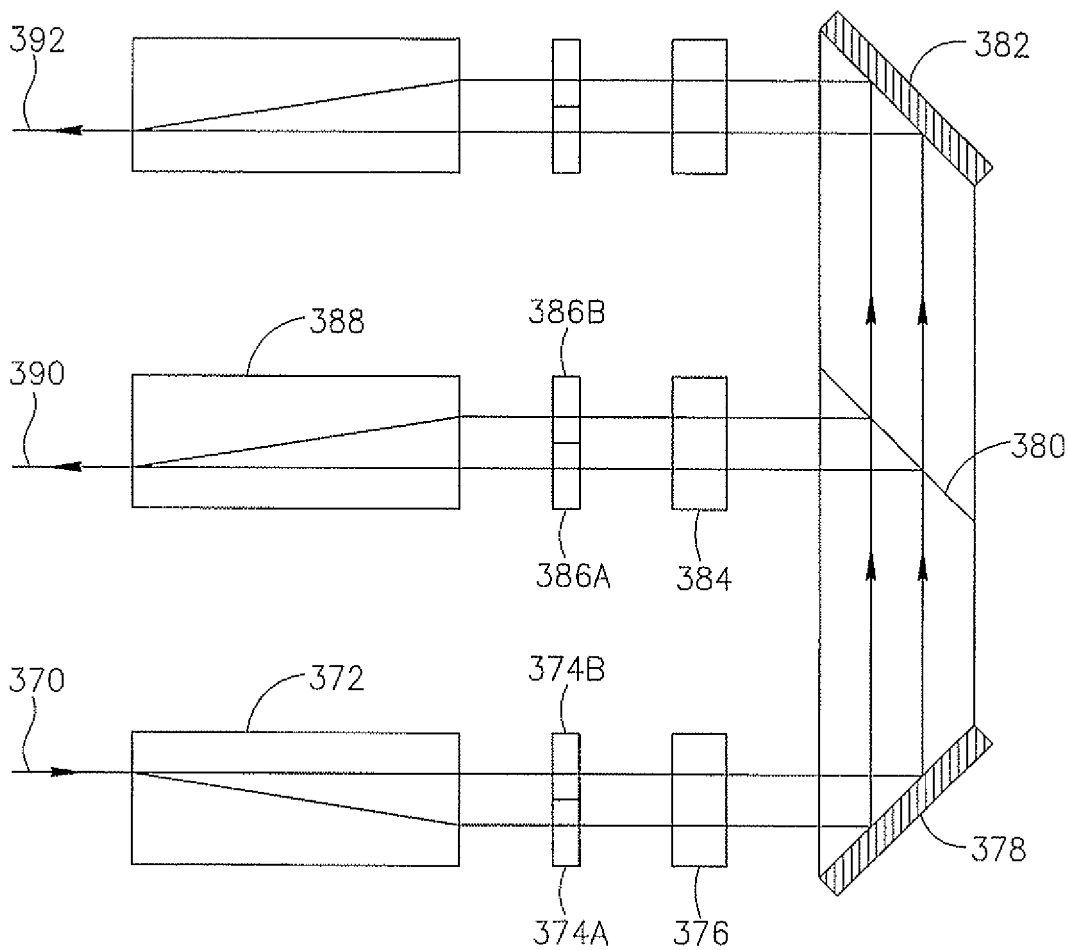
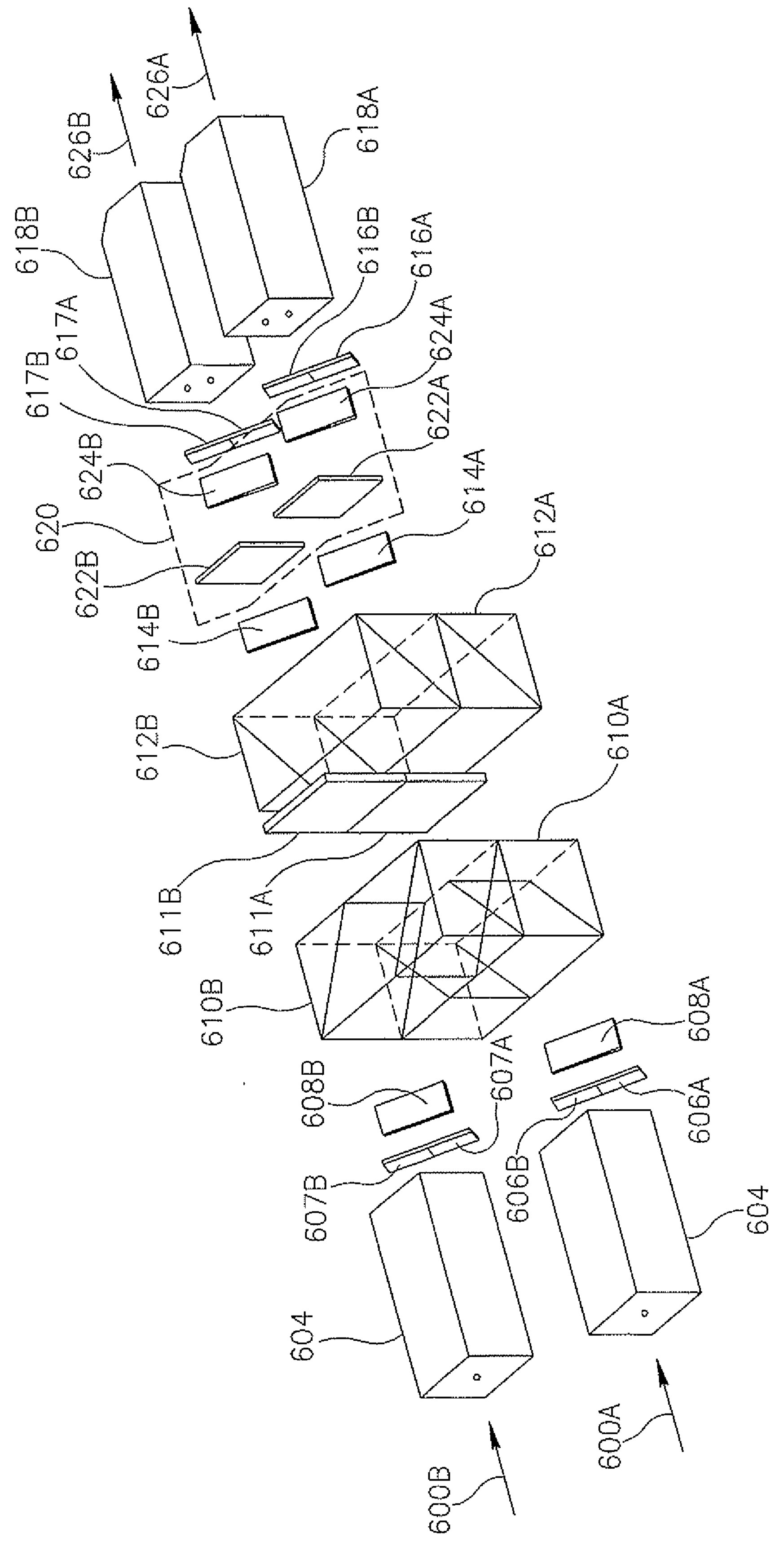



FIG.3E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600B

FIG.4

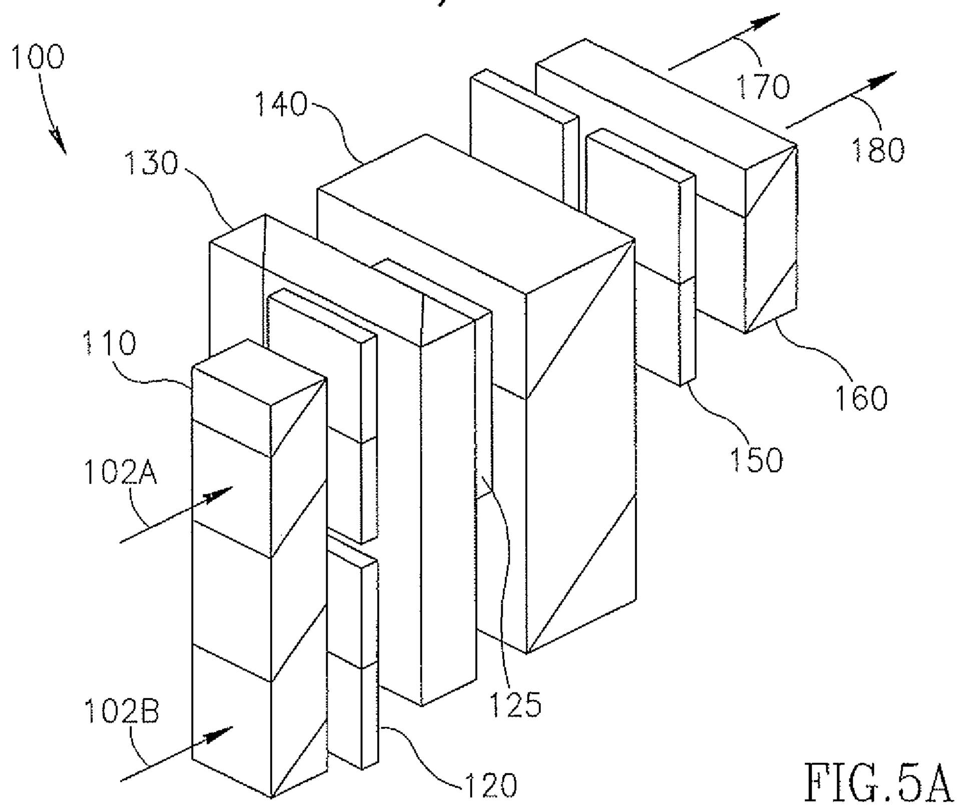
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FIG.5A

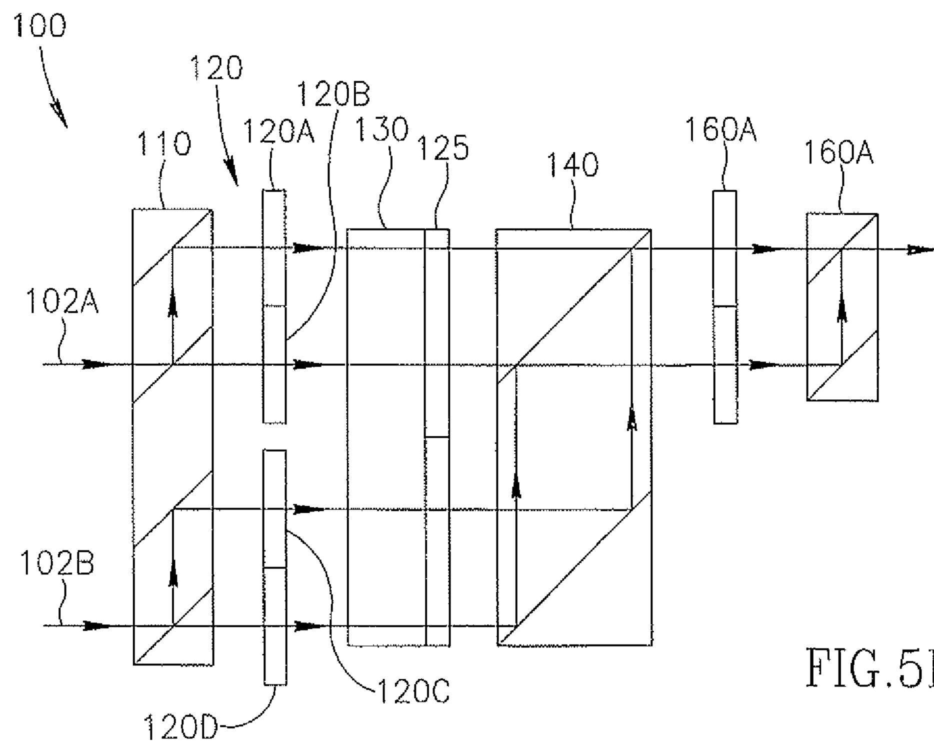
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FIG.5B

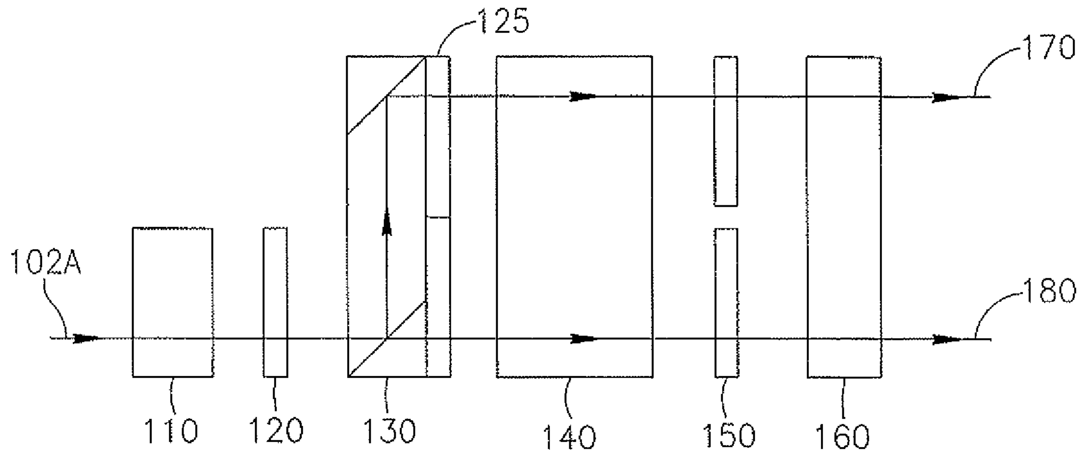



FIG.5C

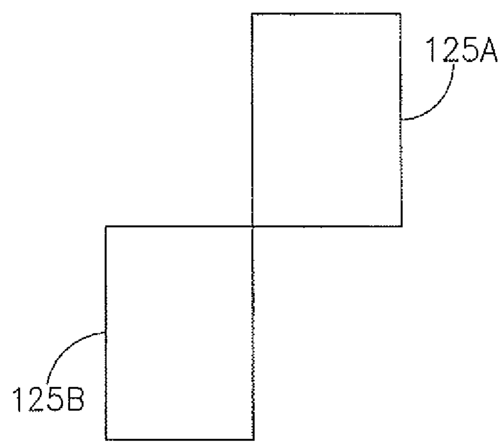



FIG.5D

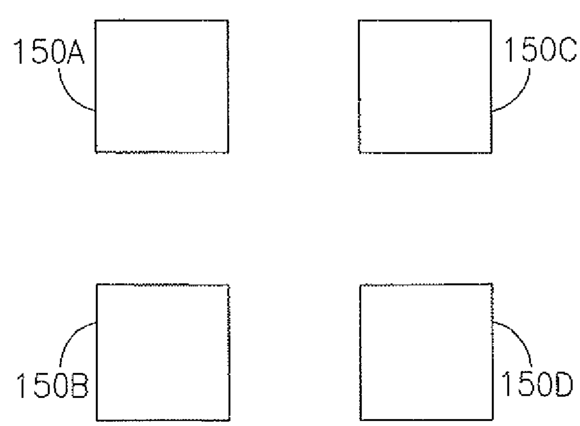
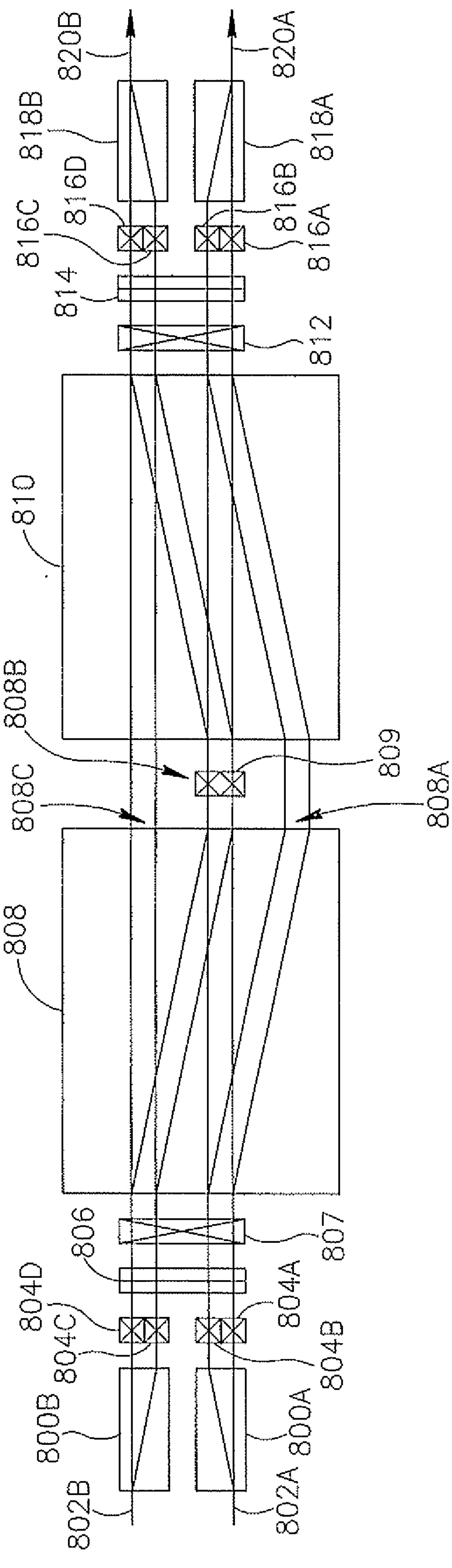



FIG.5E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802A

FIG.6

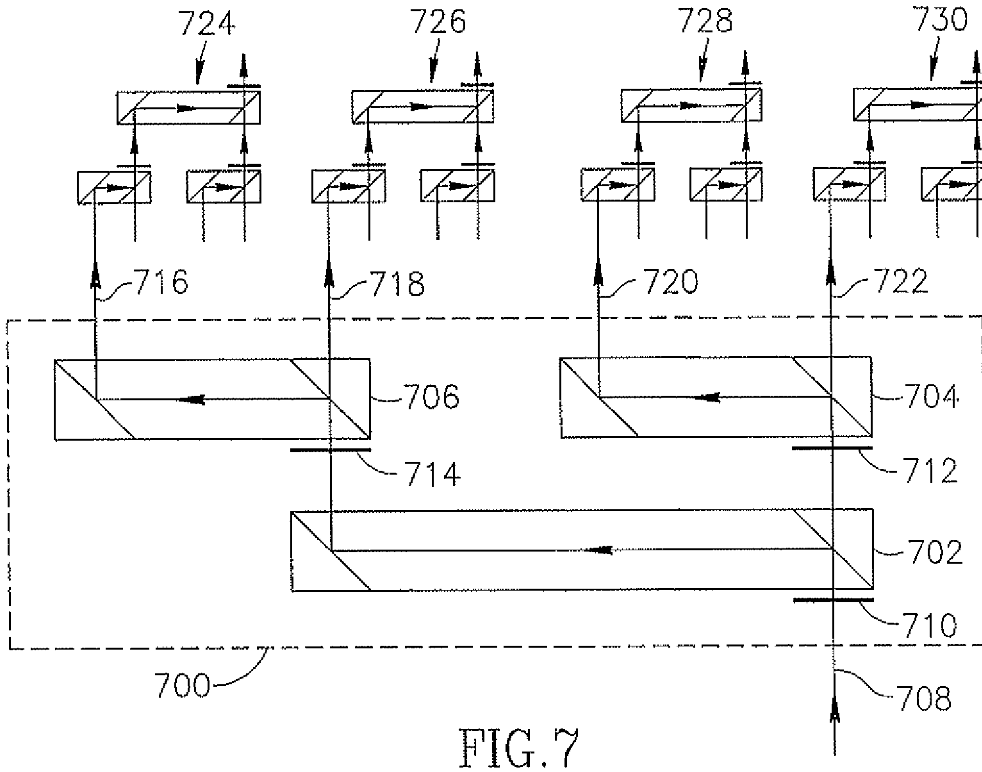


FIG.7

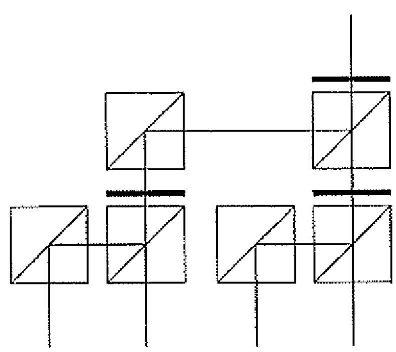

FIG.8

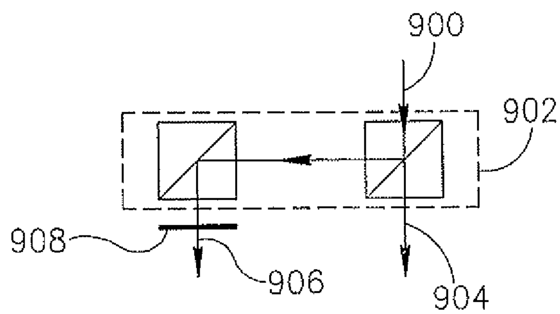


FIG.9

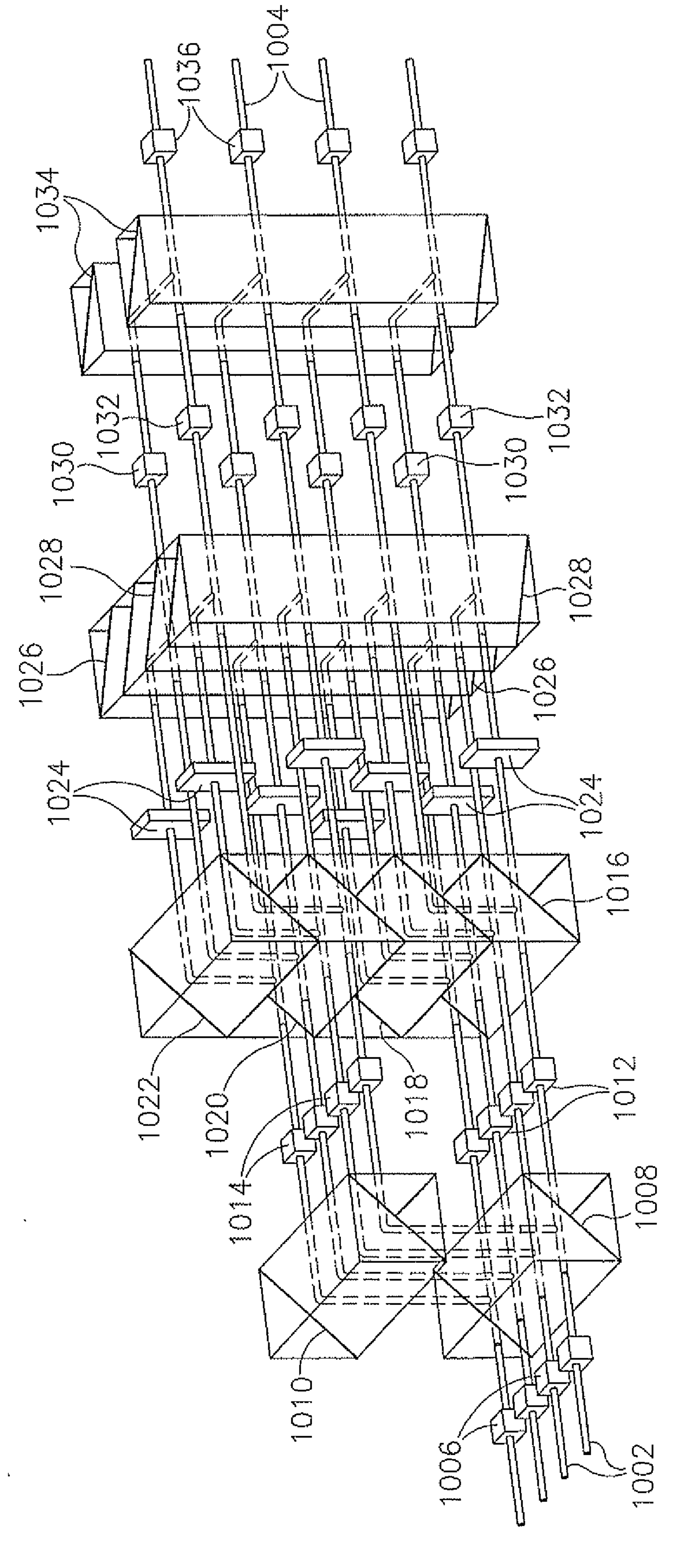
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FIG.10

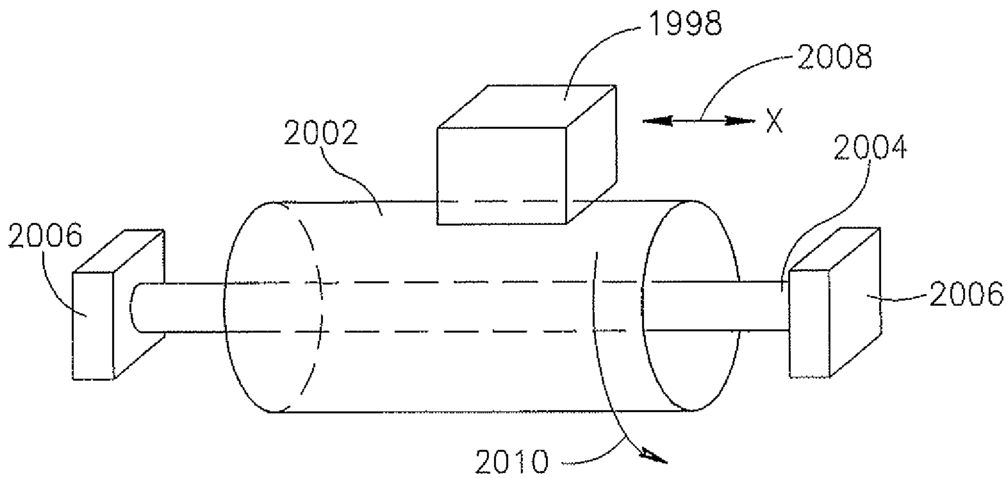


FIG.11A

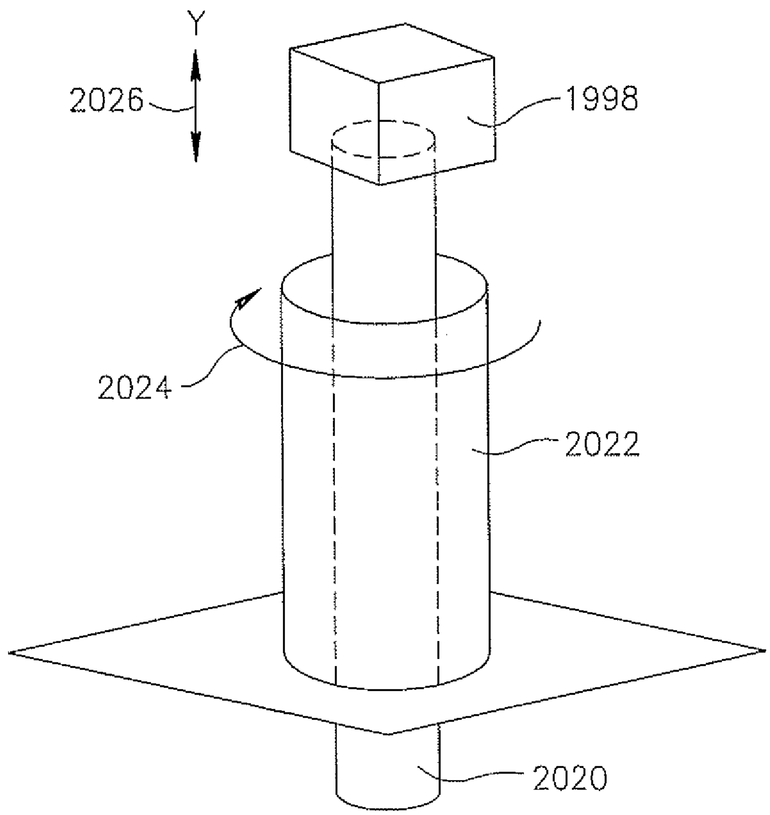


FIG.11B

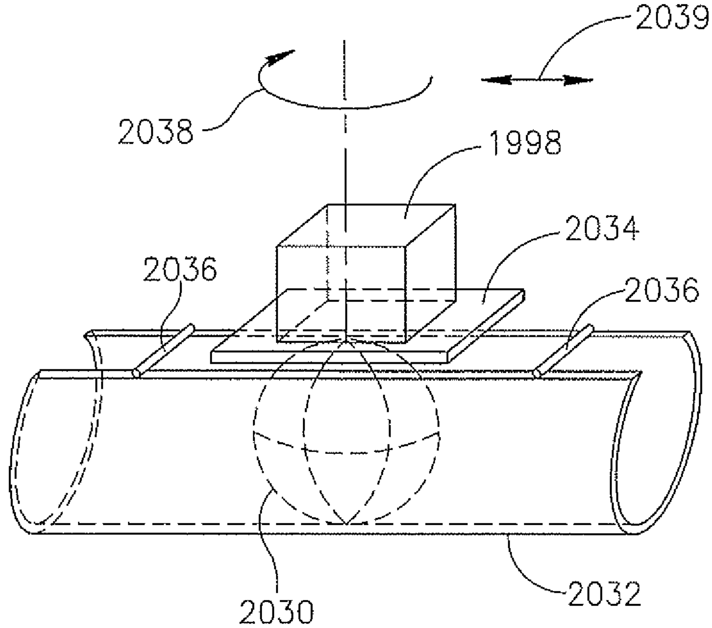


FIG.11C

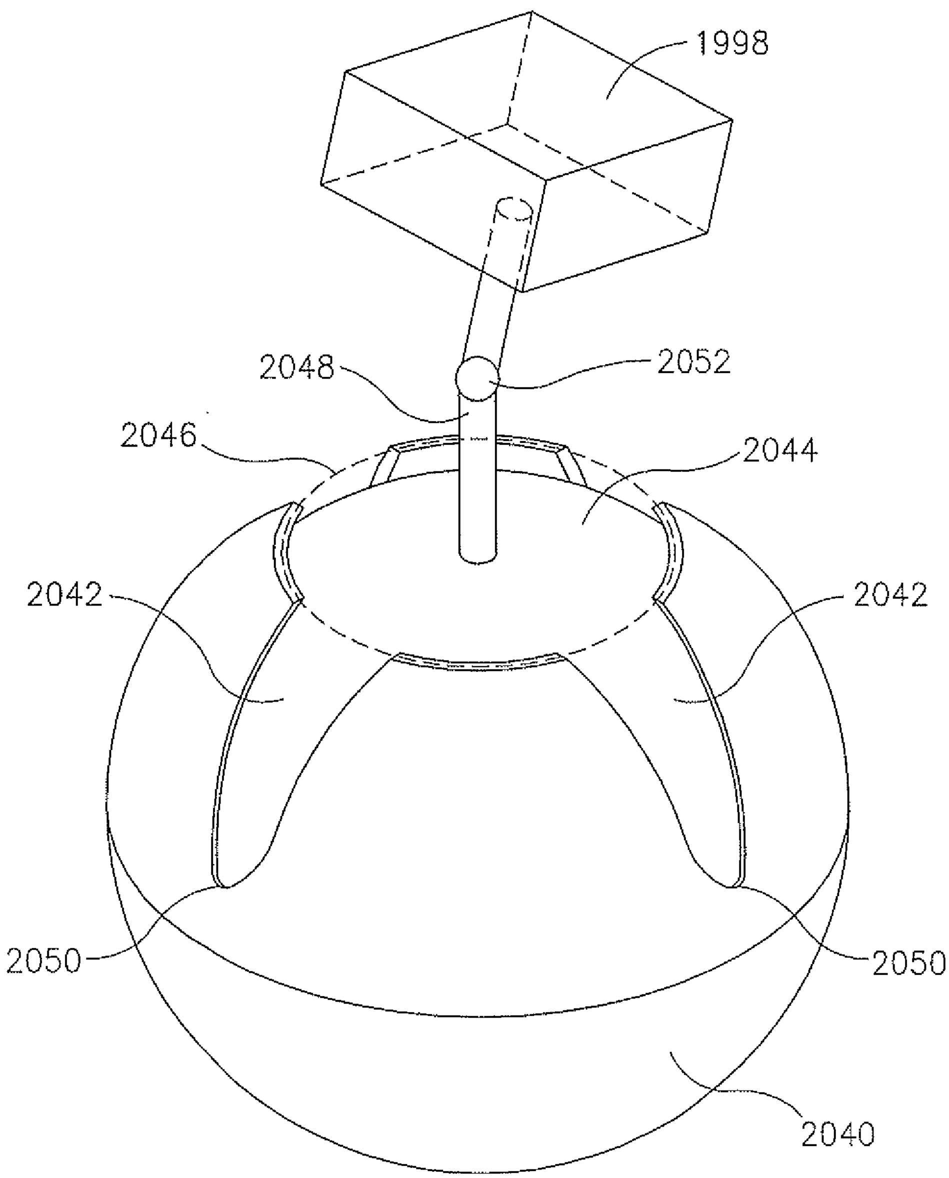


FIG.11D

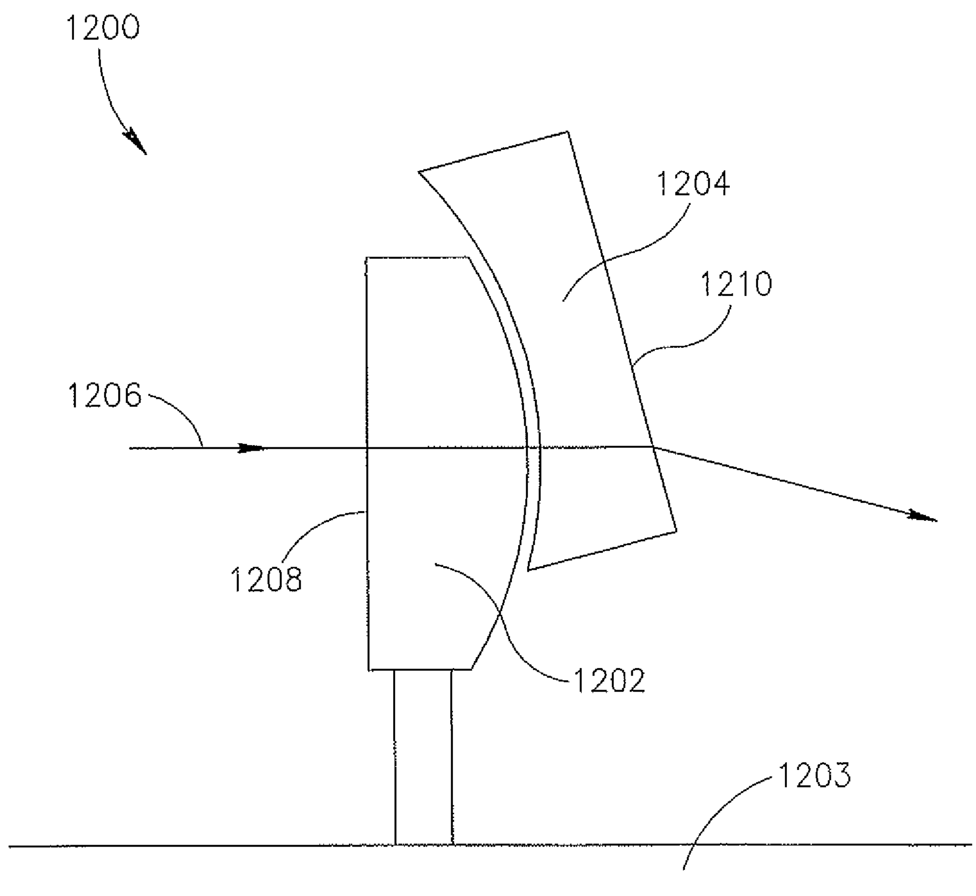


FIG.12

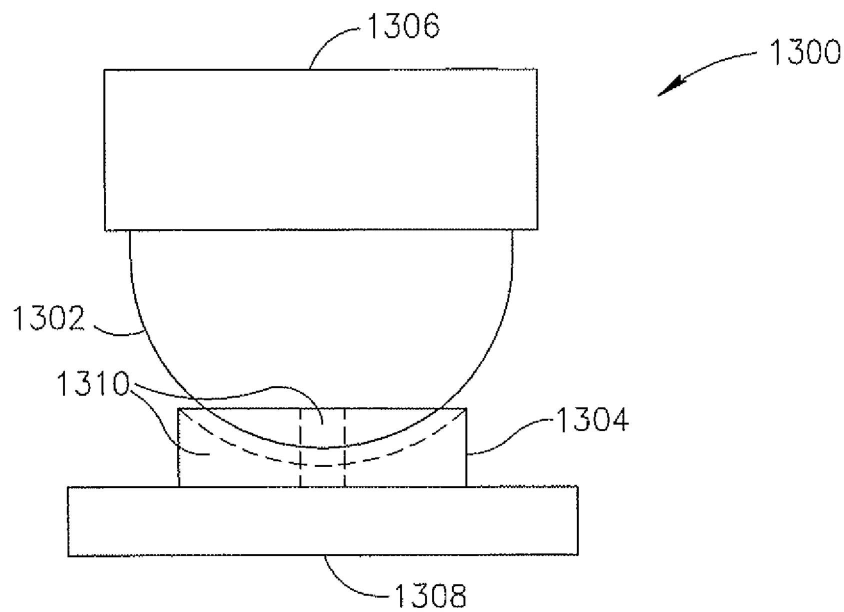


FIG.13A

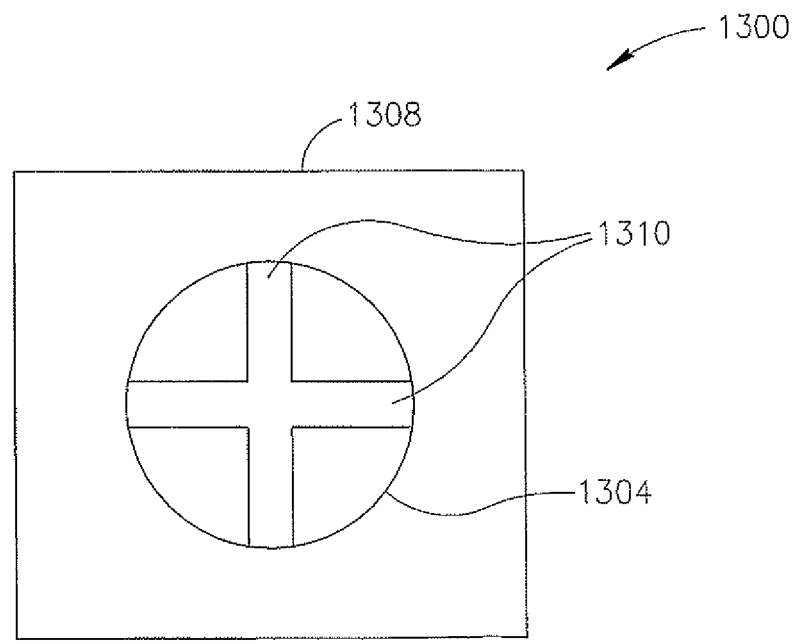


FIG.13B